

WISCONSIN HIGHWAY RESEARCH PROGRAM #0092-00-07

**Effects of Aggregate Coatings and Films
On Concrete Performance**

Final Report

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Disclaimer

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16. Abstract <p>Coarse aggregates containing surface coatings were collected throughout Wisconsin and characterized to determine composition. Based on the results of these tests, a subset of the sample aggregates was selected to further study the effects of the coatings on concrete performance. It was hypothesized that coatings consisting of clay material are more deleterious than coatings consisting of either dust or carbonate material. The 10-batch concrete mixing plan tested coarse aggregates from three different sources and in the following three conditions: (1) coated aggregates that were sampled in the field, (2) aggregates washed in the laboratory, and (3) aggregates with added coatings. The effect of each aggregate coating on concrete performance was assessed from changes in compressive strength, tensile strength, drying shrinkage, freeze-thaw durability, and chloride ion penetrability as influenced by washed versus coated aggregates. In general terms, this research suggested that the effects of aggregate coatings as sampled in Wisconsin are minor, but could not rule out the possible existence of problem aggregates not included in the small sample. The test results confirmed that coatings with a high clay contents are more deleterious to concrete strength and durability than coatings that consist largely of dust or carbonate material. While the carbonate coatings appeared to slightly improve performance, the clay coatings appeared to significantly decrease strength and durability. Although current field washing procedures do not need to be changed, it was recommended that the WisDOT consider adoption of the California Test 227.</p>			
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Executive Summary

Current Wisconsin Department of Transportation (WisDOT) specifications limit the amount of fine materials in coarse aggregates for concrete to 1.5% by mass of the total coarse aggregate. Fine materials are defined as those passing the No. 200 sieve (p200). In recent (WisDOT) projects, there has been a growing perception that the cleanliness of coarse aggregates can significantly influence the performance of portland cement concrete. Of specific concern are the silt and clay-sized particles that remain after washing and adhere to the surface of some igneous gravels. While such a perception exists, there is not hard evidence that quantifies the influence of aggregate coatings on concrete strength or durability. It is unknown whether current efforts of aggregate producers in washing aggregates to remove fine particles are sufficient or insufficient to ensure good performance.

The earliest description of surface coatings on coarse aggregates was documented by Goldbeck (1932) for the Highway Research Board. In the report, Goldbeck summarized the properties of seven different types of aggregate coatings types: stone dust, clay, organic, alkali and salt, bituminous oil, calcareous, and sugar coatings. Based on these general classifications, each aggregate coating investigated in this study was classified as a clay, dust, or carbonate coating. Clay coatings consist of clay particles that are held tightly to the aggregate surface. Because the material usually adheres to the aggregate even after the concrete is mixed, it is believed to interfere with the aggregate-cement paste bond. Unlike clay coatings, dust coatings are easily removed during mixing and affect concrete performance by increasing the amount of fines dispersed in the mix. These fines can act as pozzalonic admixtures depending on the composition of the material (Schmitt 1990). Carbonate coatings, similar to the calcareous coating type described by Goldbeck (1932), are deposited from solutions in calcite deposits and typically consist of calcium carbonate material.

It is generally believed that the effect of aggregate coatings depends on whether or not the particles adhere to the aggregate surface after mixing. Because clay fines are bound to the aggregate by electrostatic forces, many researchers suggest that clay coatings disrupt the aggregate-cement paste bond (Dolar-Mantuani 1983, Forster 1994, Schmitt 1990, Goldbeck 1932, Neville 1996). If the bond between the cement paste and the coating is stronger than the bond between the coating and the aggregate, a weak zone may develop at the coating-aggregate interface and significantly reduce concrete strength and durability (Forster 1994).

Several tests have been developed to characterize the nature of aggregate coatings. These tests include the p200 percentage, California Test 227, x-ray diffraction, and the methylene blue adsorption test. Although some of these tests are currently being used to monitor the cleanliness of coarse aggregates, most are adaptations of fine aggregate tests or are only used as research tools. These tests were chosen for evaluation in this research. The p200 percentage simply describes the quantity of material that can be removed from a coarse aggregate. The California Cleanness Test (California Test 227) provides a more vigorous procedure to remove adherent coatings and provides some distinction between clay and nonclay coatings. X-ray diffraction is a research tool to identify coating mineralogical composition. The methylene blue test detects the presence of clay particles in a sample of fine material.

Coarse aggregate deposits susceptible to coatings were identified through a survey of concrete paving contractors and WisDOT district offices. Based on the information collected in

the survey, samples were obtained from 10 aggregate sources from locations across the state. The properties of the aggregate coatings were measured using the tests identified above to determine mineralogy. Coatings were identified as dust, carbonate, and carbonate/clay compositions.

The results of the aggregate coating tests indicated that the coatings consisted largely of particles that have the same mineralogy as the source aggregate deposit. The coatings from southern Wisconsin contained mostly carbonate minerals, and the coatings from northern Wisconsin contained major amounts of feldspar minerals and minor amounts of clay. Dolomite, quartz, and anorthite are important constituents of the dolostone and quartzite deposits in the southern part of the state; albite, quartz, and amphibole are important constituents of the igneous deposits in the northern part of the state. The clay minerals found are most likely associated with the slow disintegration of the igneous rocks.

Three aggregates were chosen for subsequent tests on concrete specimens. Concrete specimens contained coarse aggregate as received from the producer and were compared with concrete specimens containing aggregate that underwent laboratory washing to further remove any adherent coatings. The first aggregate was identified as Source C from Manitowoc Cty. The low p200 percentage and high cleanness value of the Source C aggregate indicated that only a small amount of material adhered to the aggregate surface. Since the p200 percentage was 0.3%, significantly lower than the WisDOT specification limit of 1.5%, it is unlikely that the coating would cause any noticeable changes in the concrete. The low methylene blue value suggested that the coating was predominantly dolomite and provided further evidence that the coating would be innocuous. Because of the cleanliness of the aggregate, washing did not significantly change the amount or clay content of the adherent material.

The second aggregate was identified as Source E from Marathon Cty. The cleanness value and methylene blue value of the coated aggregate implied that the Source E coating contained moderate amounts of clay material. However, it was initially uncertain if the coating would be harmful because the cleanliness parameters were within the California specification requirements. Although minor amounts of illite and chlorite were identified in the coating, the cleanness value of 85 and the methylene blue value of 6.4 mg/g did not suggest deleterious effects to be likely. To increase the extent and clay content of the coating, dust fines from Barron Cty and clay fines from Sauk Cty were added to the aggregate in final batches of the test program. The feldspar minerals identified in the Barron Cty fines and the clay minerals identified in the Sauk Cty fines modified the original dust/clay coating into a dust coating and a clay coating, respectively.

The third aggregate was identified as Source H from Dodge Cty. Both the p200 percentage and methylene blue value of the coated Source H aggregate were high because the aggregate was not washed on-site before it was sampled. Despite the severity of the coating, the California cleanliness rating of the aggregate was similar to the cleanliness of the other field-washed aggregates.

The aggregates were used in 10 batches of test concrete. Mix proportions were based on the WisDOT Grade A concrete mix design. For each test batch, material quantities were determined to yield 3 ft³ of concrete with a net water-cement ratio of 0.45 and a target air content of 6.0 ± 1.0%. Hardened concrete performance was assessed by measuring the strength, durability, shrinkage, and air void distribution of each concrete batch.

Compressive strengths were determined according to ASTM C39 using 4-in. by 8-in. concrete cylinders and a 28-day wet curing period. Tensile strength was measured using the split-cylinder tension test described in ASTM C496. Drying shrinkage testing was conducted in general compliance with ASTM C490 using three concrete prisms with steel studs inserted at each end to provide a gage length of approximately 10.0 in. Freeze-thaw durability was assessed from the weight and stiffness degradation of three concrete specimens subjected to the environmental conditions specified in ASTM 666 Procedure A. The rapid chloride ion penetrability test (ASTM 1202) was used as an indicator of the permeability of each concrete batch. Petrographic concrete thin-sections of specimens from select batches were prepared by the University of Wisconsin-Madison Department of Geology and studied under a stereomicroscope following the guidelines specified in ASTM 856. To confirm results observed with the stereomicroscope and to further investigate the interfacial zone in detail, additional specimens were sent to American Petrographic, Inc. for independent evaluation.

The test results showed most aggregate coatings naturally occurring in the state to be innocuous with no identifiable influence on concrete strength or durability. However, the sample size was small and this research could not rule out the existence of coarse aggregates with problem coatings. The mineralogy of the coatings was found to be more important than quantities. Clay coatings hold the potential to be detrimental to concrete. The test results of the aggregate coatings manufactured in the lab indicated that aggregates with clay coatings and a p200 percentage near 1.5% can potentially produce noticeable changes in slump and durability. Drying shrinkage increased by approximately 65% when extensive clay coatings were present. Impacts on workability were significant and could prompt field additions of water that may negatively impact other concrete properties. There was no evidence that aggregate coatings disrupt the aggregate-cement paste bond. There was some evidence of clay coatings disrupting the air void system by concentrating air voids around coarse aggregate particles. Despite the fact that these effects may be mitigated by vigorously rewashing the aggregate until the adherent clay is removed, the resulting increases in concrete strength (5%) and durability (3%) do not appear to warrant by themselves additional aggregate washing. The research team recommends that WisDOT consider implementation of the California Cleanness Test as an improved means to sort detrimental aggregate coatings from those that are innocuous.

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1. Problem Statement

In recent Wisconsin Department of Transportation (WisDOT) projects, there has been a growing perception that the cleanliness of coarse aggregates can significantly influence the performance of portland cement concrete. Of specific concern are the silt and clay-sized particles that remain after washing and adhere to the surface of some igneous gravels. The adherent material, referred to as an aggregate coating, results from the weathering and processing of aggregates and is often difficult to remove. Wisconsin engineers and concrete pavers have speculated that these coatings negatively impact concrete strength and durability. Researchers suggest these coatings may reduce the aggregate-cement paste bond and disrupt the air void system. Specific examples of the perceived aggregate coating problems provided by WisDOT engineers are listed below:

1. Coatings, presumably clay, adhering to igneous gravel in northern Wisconsin have been used in unusually stiff concrete mixtures, giving the impression that the cement was defective.
2. An unidentified coating type in southeastern Wisconsin was responsible for cracking at the aggregate-concrete interface. The adhering strength of the coating was strong enough to survive vigorous washing.
3. Coatings on crushed limestone aggregate have been blamed for low strength concrete in southern Wisconsin.

The general locations of these problematic aggregates are shaded in Figure 1.

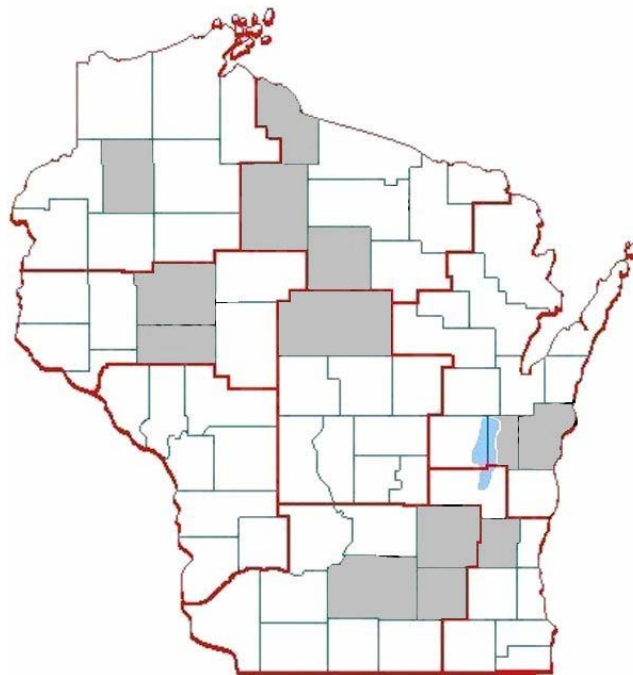


Figure 1. Locations of Suspected Deleterious Aggregate Coatings

Because the effects of aggregate coatings on concrete performance are poorly understood, specifications restricting their use tend to be vague. For instance, the WisDOT specifications require coarse aggregates to be “clean” and “free of adherent coatings which

could be considered injurious” but do not define what coatings are injurious or how they should be washed (WisDOT 1996). A better understanding of the nature of aggregate coatings may have an impact on the economics of aggregate processing. Identifying which coatings are harmful may indicate when more rigorous washing is required, while identifying which are harmless may indicate when washing procedures can be relaxed.

2. Objectives and Scope of Research

The purpose of this research was to investigate the nature of aggregate coatings in Wisconsin and determine their effects on concrete strength and durability. Final objectives of the study are listed below:

1. Determine the mineralogy of aggregate coatings found in Wisconsin.
2. Measure the effects of coatings on concrete strength and durability.
3. Evaluate the effectiveness of aggregate washing.
4. Identify test methods to monitor aggregate cleanliness.

The research program was divided into three phases: review of existing literature (Phase I), characterization of aggregate coatings in Wisconsin (Phase II), and laboratory testing and analysis of concrete batches containing coated and washed aggregates (Phase III).

The main hypothesis developed by the research team was that WisDOT specifications should distinguish between coatings that contain significant amounts of clay material and coatings that are predominately stone dust or carbonate material. Clay minerals are different from non-clay minerals because of their platy particle shape and net negative charge. Due to these unique properties, clay coatings are potentially more injurious to concrete because of their moisture sensitivity and tight adherence to coarse aggregate particles.

The coarse aggregates examined in the study were limited to deposits in Wisconsin where coatings were perceived to exist. Most of the samples were taken from stockpiles of ¾-in. washed stone that met the gradation and deleterious substance requirements of the Wisconsin Department of Transportation. As a result, the initial amount of material passing the No. 200 sieve did not exceed 1.5% by mass. Since it is not the intent of this study to endorse or discredit aggregates produced from any specific supplier or quarry, the aggregate sources cited in this report are identified by region but not by specific quarry names.

3. Background and Summary of Existing Literature (Phase I)

3.1 Descriptions of Aggregate Coatings

The earliest description of surface coatings on coarse aggregates was documented by Goldbeck (1932) for the Highway Research Board. In the report, Goldbeck summarized the properties of seven different types of aggregate coatings types: stone dust, clay, organic, alkali and salt, bituminous oil, calcareous, and sugar coatings. More recently, several researchers have organized these coating types into more general classifications. Lang (1943) divided coatings into three categories – clay, dust, and cementation coatings – depending on their mineralogy and strength of adherence. A similar classification was given by Schmitt (1990) who distinguished between dust, cementation-type, and impregnation-type coatings.

Based on these general classifications, each aggregate coating investigated in this study was classified as a clay, dust, or carbonate coating. Clay coatings consist of clay particles that are held tightly to the aggregate surface. Because the material usually adheres to the aggregate even after the concrete is mixed, it is believed to interfere with the aggregate-cement paste bond. Unlike clay coatings, dust coatings are easily removed during mixing and affect concrete performance by increasing the amount of fines dispersed in the mix. These fines can act as pozzalonic admixtures depending on the composition of the material (Schmitt 1990). Carbonate coatings, similar to the calcareous coating type described by Goldbeck (1932), are deposited from solutions in calcite deposits and typically consist of calcium carbonate material.

In addition to classifications that group coatings by composition or strength of adherence, researchers have also classified aggregate coatings according to their source (Ozol 1979, Forster 1994). Coatings deposited by water are mostly mineral in nature and include calcium carbonate, iron oxide, gypsum, and alkali sulfates. Coatings containing clay, silt, and organic matter are found naturally in the overlying layers of the deposit or are artificially placed on the aggregate during processing. These classifications were not used to describe the sampled aggregate coatings, however, because the focus of this research was on the mineralogy of Wisconsin aggregate coatings rather than their origin.

3.2 Effect of Coatings on the Aggregate-Cement Paste Bond

It is generally believed that the effect of aggregate coatings depends on whether or not the particles adhere to the aggregate surface after mixing. Because clay fines are bound to the aggregate by electrostatic forces, many researchers suggest that clay coatings disrupt the aggregate-cement paste bond (Dolar-Mantuani 1983, Forster 1994, Schmitt 1990, Goldbeck 1932, Neville 1996). If the bond between the cement paste and the coating is stronger than the bond between the coating and the aggregate, a weak zone may develop at the coating-aggregate interface and significantly reduce concrete strength and durability (Forster 1994).

The link between coatings and the aggregate-cement paste bond dates back to Goldbeck (1932) who cited research by the National Crushed Stone Association that examined the effect of stone dust on concrete strength and wear resistance. In the study, dust coatings were created by moistening the coarse aggregate and adding fines from granite, limestone, or gneiss rock in amounts up to 5.7% of the coarse aggregate weight. It was believed that the dust would either adhere to the aggregate and disrupt the aggregate-cement paste bond or separate from the aggregate and form a weak layer at the surface of the concrete. While the dust did not significantly affect the wear resistance, it did influence the strength of the concrete. For each 1% increase in the amount of dust, the compressive strength decreased between 0% and 2% and the modulus of rupture decreased between 1% and 1.5%.

The contribution of mechanical interlocking to the strength of the aggregate-cement paste bond was studied by Darwin and Slate (1970) who compared concrete mixed with an aggregate coated with polystyrene and concrete mixed with an uncoated aggregate. The researchers theorized that the quality of the bond was related to the penetration of cement

paste into the pores of the aggregate (see also Dolar-Mantuani 1983). In the experiment, the strength of the aggregate-cement paste bond was measured using aggregate prisms encased in a cement paste briquette. It was assumed that the polystyrene coating would significantly decrease the bond strength and, in turn, decrease the strength and stiffness of the concrete. However, Darwin and Slate found that the coating only slightly reduced concrete strength (10%-15%) despite causing large reductions in bond strength (60%-95%).

In a similar study, Patten (1973) tried to investigate the relationship between bond strength and the surface chemistry of the aggregate. Using a non-adhesive silicone release agent, a thin coating was placed around the aggregate to disrupt any chemical reactions in the interface zone. While Patten assumed that the coating eliminated adhesive bonds without affecting the mechanical interlock, Struble, Skalny, and Mindess (1980) questioned the assumption and suggested experimental verification. On average, the silicone coating decreased compressive strength by 25% and tensile strength by 17%.

Although many conclude that aggregate coatings weaken the aggregate-cement paste bond, there is little experimental evidence that directly supports the claim that this effect reduces concrete strength and durability. In fact, a literature review on the aggregate-cement paste bond reports some controversy regarding the relationship between bond strength and concrete performance (Struble et al. 1980). Some researchers suggest that poor bonding allows microcracks to propagate at a lower stress, while others believe that the stress level of microcrack propagation does not affect the ultimate concrete strength (Struble et al. 1980). Because it is nearly impossible to isolate the contribution of the aggregate-cement paste bond to concrete strength, studies investigating the bond using comparative compression and tensile bond strength tests have had limited success proving the premise. Yet there are not suitable alternatives to these tests and the difficulty of isolating the effect on strength confirms that the effect is generally small. Although the strength of the aggregate-cement paste bond has been measured in previous research by applying adhesive coatings to coarse aggregate particles, the coatings have influenced the results by changing the stiffness properties of the concrete. In recent research, this problem has been overcome by examining the characteristics of the interfacial bond with finite element models. Using this method, Darwin (1999) estimated that the greatest effect of interfacial bond strength on compressive strength is 15%, which is less than the estimates of previous researchers.

3.3 Effect of Coatings as Dispersed Fines

If coatings are removed during mixing, fine particles that were not accounted for when the aggregates were batched are dispersed into the concrete. These dispersed fines can be either beneficial or detrimental to concrete strength depending on the quantity and mineralogy of the added material. Dust fines can either increase strength by accelerating hydration or decrease strength by increasing water demand (Bonavetti and Irassar 1994). According to Hughes and Ash (1986), amounts of dust fines within current aggregate specifications are usually acceptable in concrete. On the other hand, significant amounts of dispersed clay fines are unacceptable because they increase the water demand of the aggregate and prevent adhesion to the cement paste (Pike 1992). Pike suggests the following rules-of-thumb to estimate the effect of clay fines on concrete strength:

1. An addition of 1% kaolinite by mass of cement causes a loss of strength of 1%.
2. An addition of 1% illite by mass of cement causes a loss of strength of 2%.

3. An addition of 1% montmorillonite by mass of cement causes a loss of strength of 4%.

One of the earliest studies that investigated the effects of fines in concrete was led by researchers at the University of Colorado (Goldbeck 1932). During the study, crushed granite dust was dispersed in the fine aggregate just before mixing. When the water absorption of the added fines was ignored in the mix design, the slump decreased and the concrete strength increased. However, when the water absorption of the fines was controlled by keeping the slump constant, the gross water-cement ratio increased and the concrete strength decreased. The researchers found that a compromise between maintaining reasonable workability and limiting water additions canceled out any influence on strength for dust additions up to 15% to 20% of the fine aggregate portion.

Anecdotal evidence reported by Davis, Mielenz, and Polivka (1967) suggests that clay particles can also affect concrete by reacting chemically with the cement. During the construction of a dam in a Western state, engineers and contractors became concerned when the slump of the concrete decreased between 60% and 80% within the first 15 minutes of mixing. At first, it was believed that defective cement produced a false set; however, it was later discovered that the sand contained significant amounts of montmorillonite. A petrographic examination revealed that the sand, taken from a previously undeveloped, deeply weathered glacial deposit, was contaminated with coatings and dispersed particles of very fine clay grains and mineral dust. After a series of lab tests, it was concluded that the clay material reacted with the hydrating cement and adsorbed significant amounts of water.

Noble (1967) described the reactions between clay and cement in more detail based on his research on stabilized soils. In clay-cement mixtures containing kaolinite, illite, or montmorillonite, Noble suggested that the clay particles impair hydration by encapsulating and reacting with cement compounds. Noting this interaction, Pike (1992) theorized that the loss of strength in mortars containing clay fines is caused by clays adsorbing part of the mix water and forming “impermeable envelopes” around the cement grains. Ultimately, these effects slow hydration and disrupt the adhesion of the fines to the cement.

3.4 Aggregate Coating Test Methods

Several tests have been developed to characterize the nature of aggregate coatings. These tests are the p200 percentage, California Test 227, x-ray diffraction, the methylene blue adsorption test and the use of Atterberg limits. Although some of these tests are currently being used to monitor the cleanliness of coarse aggregates, most are adaptations of fine aggregate tests or are only used as research tools.

The p200 percentage represents the amount of silt and clay sized particles retained from a coarse aggregate sample removed by washing the aggregate washed over a No. 200 sieve and is the most common method of controlling aggregate coatings. In Wisconsin, the state specification limits the amount of p200 material from a coarse aggregate to 1.5% (WisDOT 1996). A similar restriction is recommended in the ASTM standard (ASTM C33), although the allowable percentage ranges from 1.0% to 1.5% depending on the amount of clay in the aggregate and the cleanliness of the fine aggregate. Despite its widespread use in aggregate specifications, the p200 percentage may not accurately measure the extent of the coating because it includes fines dispersed in the aggregate and excludes strongly

adhering particles that might not be removed during the washing procedure. In addition, the test does not distinguish between fines that may not affect concrete performance, such as some types of stone dust, and those that are harmful to concrete performance, such as swelling clay particles.

The California Cleanness Test (California Test 227), similar to the sand equivalent test for fine aggregate (ASTM D2419), measures the relative amount of clay-sized particles clinging to the aggregate. In the test, adherent material is removed by mechanically washing a sample of coarse aggregate in a special container. After collecting the wash water that passes through a No. 200 sieve, the water is placed in a graduated cylinder and mixed with a solution of glycerin and calcium chloride. The height of the sediment that settles at the bottom of the graduated cylinder after 20 minutes is translated into a cleanness value from 0 (dirtiest) to 100 (cleanest). A minimum cleanness of value of 75 is specified by the California Department of Transportation (California, 1999), which uses the test to measure aggregate cleanliness instead of the p200 test. Unlike the p200 percentage, which only measures the amount of silt and clay in the sample, the cleanness value indicates the quantity, particle size, and activity of the material adhering to the aggregate (Benson and Ames 1975). A copy of California Test 227 is located in Appendix A.

X-ray diffraction identifies the mineral phases in a powder sample from the pattern of waves diffracted through a crystalline structure. The analysis is qualitative because it is extremely difficult to determine the quantities of each identified mineral unless a limited number of different phases are present and rigorous standardized procedures are followed. During the test, x-rays are passed through the sample and collected by a detector, which measures the angle and intensity of the x-ray reflections (Gillot 1987). The spacing between planes of atoms in the crystal is calculated from the wavelength of the x-rays and the angle of diffraction according to Bragg's Law. The intensity of x-ray reflections at each interplanar spacing determines the diffraction pattern of the sample. By matching the diffraction pattern to a database of known patterns, the presence of each mineral or compound can be identified (St. John et al. 1998). Although the percentage of each mineral can be estimated by comparing the areas under the peaks in the x-ray diffraction pattern, calculating the exact quantities is nearly impossible. Due to the sophistication of the equipment, x-ray diffraction is not widely used to control aggregate coatings. However, it is a potentially valuable tool for research and forensic investigations because it can classify aggregate coatings as dust coatings, clay coatings, or carbonate coatings following the descriptions of Goldbeck (1932) and Lang (1943).

The methylene blue adsorption test uses the unique properties of clay minerals to measure the relative amount of clay in a sample of aggregate. The procedure consists of titrating a mixture of water and p200 material with methylene blue dye, a cationic solution that is adsorbed to the surface of clay minerals (Bernsted 1985). This end-point, or the point at which the sample no longer adsorbs the dye, is observed when a light blue halo surrounds a drop of the mixture after it has been placed on filter paper. Based on the volume of dye used in the titration, a methylene blue value (MBV) is calculated for the sample.

$$\text{MBV} = \frac{\text{solution concentration} \times \text{titration volume}}{\text{sample mass}} \quad [1]$$

Because the sample mass in the above equation represents the p200 material removed from an aggregate sample, the modified methylene blue value (MMBV) should be used to indicate the overall clay content of the aggregate (Tourenq and Tran 1997).

$$\text{MMBV} = \frac{\% \text{ p200}}{100} \times \text{MBV} \quad [2]$$

The methylene blue test is well suited to investigations of aggregate coatings because it can detect the presence of harmful clay particles. Since only clay minerals can exchange cations, the dye is adsorbed by clay coatings but not by dust and carbonate coatings, which consist of minerals like quartz, feldspar, dolomite, and limestone (Bernsted 1985). The amount of dye adsorbed is related to the activity and specific surface of the coating and may be used to determine its water demand. In the French concrete specifications, the methylene blue value of fines extracted from fine aggregate is limited to 10 mg/g (Pike 1992). In England, Pike proposed a maximum value equivalent to 20 mg/g after assessing the cleanliness and variability of over 200 washed and unwashed sands. Although the test could potentially be used to identify harmful aggregate coatings, its poor repeatability may limit its practical use as a quality control test. According to Pike (1992), the coefficient of variation associated with the repeatability and reproducibility of the test is 20% and 30%, respectively.

The Atterberg limits denote the transformation of clay material from a solid to a viscous liquid due to water additions. The plasticity index, the difference between the liquid limit and plastic limit, represents the range of plasticity of the material and has been used to characterize soils and aggregates used in the geotechnical and asphalt industries. The plasticity index is related to the type and amount of clay minerals in the sample since the plasticity of a material is caused by the water held to the surface of the clay particles. Because clay minerals are concentrated in the clay-sized fraction ($< 2 \mu\text{m}$), the measured plasticity is lower if a significant amount of coarse particles is present. As a result, it is important to note whether the Atterberg limits are measured for samples passing the No. 40 sieve or the No. 200 sieve. Although the test is being used in some asphalt aggregate specifications, there is no reported correlation between the plasticity index and asphalt performance (Kandhal and Parker 1998). Because little research has focused on the correlation between the Atterberg limits and concrete performance, the tests are not often considered promising aggregate quality control tests.

4. Methodology for Phases II and III

4.1 Aggregate Sampling for Phases II and III

Coarse aggregate deposits susceptible to coatings were identified through a survey of concrete paving contractors and WisDOT district offices. A copy of the survey and a list of the participants can be found in Appendix B. Based on the information collected in the

survey, samples were obtained from the 10 aggregate sources with locations shown in Figure 2 to get a general idea of the types of aggregate coatings found in Wisconsin.

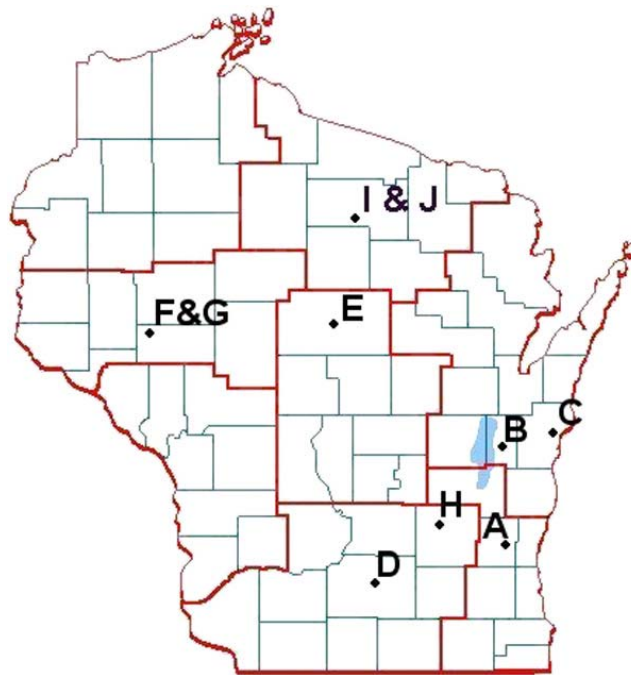


Figure 2. Locations of Aggregate Sources Sampled

In many cases, sampling was hindered by the sensitivity of aggregate producers and the variability of cleanliness within the deposit. For some of the suspect aggregate sources, owners refused to participate in the study, and for others the sampled aggregate was virtually free of any adhering coating. The latter problem may derive from varying perceptions of what constitutes a deleterious aggregate coating or from the fact that coatings are often isolated in a specific seam of a deposit. To offset the sources that declined involvement in the research, samples were collected from alternative sites in the same region.

In Phase II, the samples from the 10 locations were tested to measure the extent and nature of any existing coatings. Based on Phase II results, larger samples were collected in Phase III from Source C, E, and H to evaluate the effects of the coated aggregate on concrete performance. These aggregates were selected to vary the level and mineralogy of the coatings investigated in the study. The concrete batches were divided into three series of mixes. Batches 1-3 (Coated Aggregate Series - Field) included the coated aggregates sampled from aggregate stockpiles at Sources C, E, and H. Batches 4-6 (Washed Aggregate Series - Lab) tested aggregates C, E, and H after the adherent coatings were removed in the laboratory with additional washing. Batches 7-10 (Coated Aggregate Series - Lab) contained aggregate from Source E that was artificially coated with dust and clay fines to increase the extent or clay content of the coating. For Batches 7 and 8, the manufactured coating consisted of stone dust collected from a sedimentation pond at a

Barron Cty gravel pit. For Batches 9 and 10, the attached coating consisted of a clayey material that was dry sieved from a Sauk Cty soil. A summary of the mixing plan is shown in Table 1. As shown in the table, each of the basic aggregate coating types was included in the research.

Table 1. Summary of Mixing Plan

Batch	Aggregate Source	Coating Type
<i>Coated Aggregate Series - Field</i>		
1	C - Manitowoc Cty	Carbonate
2	E - Marathon Cty	Dust/Clay
3	H - Dodge Cty	Carbonate/Clay
<i>Washed Aggregate Series - Lab</i>		
4	C - Manitowoc Cty	Carbonate
5	E - Marathon Cty	Dust/Clay
6	H - Dodge Cty	Carbonate/Clay
<i>Coated Aggregate Series - Lab</i>		
7	E - Marathon Cty	Dust
8	E - Marathon Cty	Dust
9	E - Marathon Cty	Clay
10	E - Marathon Cty	Clay

Concrete testing included slump and air content measurements on fresh concrete and compressive strength, tensile strength, shrinkage, freeze/thaw durability, and rapid chloride ion penetrability measurements on hardened concrete samples.

4.2 Aggregate Coating Characterization Tests

The properties of the aggregate coatings were measured using the tests summarized in Table 2. During Phase II, the tests were used to determine mineralogy; during Phase III, the tests were used to quantify the extent and mineralogy of aggregate coatings on concrete performance.

Table 2. Summary of Aggregate Coating Tests

Aggregate Coating Test	Standard	Tests per Batch	Phase of Study
Material Finer than No. 200 Sieve	ASTM C117	3	Phase III
California Cleanness Test	California Test 227	3	Phase II and III
Methylene Blue Adsorption Test	AASHTO TP 57	3	Phase II and III
X-ray Diffraction	UW-Madison	3	Phase II

The procedure used to determine the amount of material passing the No. 200 sieve conformed to ASTM C117. In the test, the required sample mass was collected from a batch of oven-dried aggregate and placed in a stainless steel container. The contents of the container were then charged with water, shaken vigorously, and decanted over a No. 200 sieve. The process was repeated until the resulting wash water was clear. The material that was retained on each sieve was flushed into a drying pan and dried at 230°F to compute the p200 percentage.

The California Cleanness Test was conducted in general compliance with the standard procedure in California Test 227. During the test, a 2500-g sample of oven-dried aggregate was placed in a stainless steel washing vessel with 1000 g of distilled water. After the aggregate soaked for 1 minute, the vessel was clamped shut and agitated in a sieve shaker for 2 minutes. The fines in the container were then brought into suspension and passed through a No. 8 and No. 200 sieve nested over an 8-in. diameter collection pot. To ensure that all the p200 material was collected, parts of the wash water were passed through the No. 200 sieve until the water flowed freely through the sieve. Subsequently, a sand equivalent test cylinder, marked with 150 graduations, was filled to the 3-unit mark with a calcium chloride solution and to the 150-unit mark with the wash water. After the mixture was allowed to stand for 20 minutes, the sediment height in the cylinder was recorded and translated into a cleanness value according to the tabulated relationship in the standard.

The procedure of the methylene blue adsorption test was based on AASHTO TP 57, which is currently being used in several states to test asphalt aggregates (Kandhal and Parker 1998). Prior to testing, the p200 coating was collected by mechanically washing the coarse aggregate according to California Test 227 and evaporating the wash water at 140°F. For each test, 10 g of the removed p200 material was dispersed in 30 g of distilled water using a magnetic stirrer. The suspension was then titrated with a 5-mg/mL methylene blue solution added from a buret in 0.5-mL increments. After the suspension was stirred for 1 minute, a drop of the slurry was sampled using a glass stirring rod and placed on a piece of filter paper to observe the appearance of the drop. A light blue halo around the drop indicated that the suspended fines were no longer absorbing dye, i.e. the end-point of the titration. When the halo was first observed, the sample was stirred for 5 minutes and tested again. Smaller increments of solution were added as needed until the halo remained visible for 5 minutes. Because the blue halo is often difficult to distinguish, the filter paper was held up to a 60W light bulb or observed through a magnifying glass to assist in determining the end-point of the titration. After the 5-minute blue halo was observed, the total volume of

added dye was recorded and used to calculate the methylene blue value and modified methylene blue value.

The method used for x-ray diffraction analysis was based on a general test procedure developed by the University of Wisconsin-Madison Department of Geology. Before the analysis, p200 material from the aggregate coating was ground in acetone with an agate mortar and pestle. As in the methylene blue adsorption test, these samples were collected by mechanically washing the coarse aggregate with distilled water and evaporating the resulting wash water. After carefully mounting the acetone slurry onto a glass slide, the sample was scanned over a 2θ range from 5° to 65° at a rate of 1° per minute using a Scintag PadV X-ray diffractometer. During the analysis, a computer program was used for data acquisition and peak identification. Unknown crystalline phases present in the sample were identified by matching the diffraction pattern to the patterns stored in the International Center for Diffraction Data (ICDD) database. Construction Technology Labs was contracted by the University of Wisconsin to verify the results obtained for some of the tested samples.

4.3 Coarse Aggregate Processing in Phase III

The aggregate washing procedure used to remove the adherent coatings in the laboratory was modeled after California Test 227. During the procedure, approximately 100 lbs of the coated aggregate was placed in a 1.5-ft³ mixer with 50 lbs of water. After the aggregate soaked in the mixer for 1 minute, the drum was positioned at an angle of 45° and allowed to rotate for 2 minutes. Subsequently, the suspended fines were decanted from the aggregate and a fresh 50 lbs of water was poured into the mixer. Following six washing cycles, any remaining fines were removed from the aggregate by rinsing the sample over a No. 100 sieve cloth. The material that was washed through the sieve was discarded except for a few small samples collected for methylene blue tests. For each batch, a total of 400 lbs of aggregate was washed and air-dried in a mixing pan lined with a plastic sheet before mixing.

The procedure used to create the manufactured coatings consisted of mixing the aggregate and a certain amount of the Barron Cty or Sauk Cty material to reach a desired p200 value. In each case, 400 lbs of the coarse aggregate was placed in a 3-ft³ mixer and mixed with water until the moisture content of the aggregate was slightly above the SSD condition. Once the mixer was turned on, the measured amount of fines was sprinkled on the aggregate along with an additional 10% of material to offset the material that adhered to the drum of the mixer. During mixing, the drum was positioned at an angle to limit the abrasion of aggregate against the sides of the mixer. After the fines were evenly dispersed, the coated aggregate was placed on a plastic sheet and air-dried to match the moisture contents of the aggregate used in the first two series of mixes.

To ensure a constant water-cement ratio, the amount of water added in each concrete batch was adjusted by the absorption (ASTM C127, C128) and moisture contents (ASTM 566) of the aggregates. The moisture content of the fine aggregate was controlled by oven drying prior to batching. To minimize potential alterations to the aggregate coatings caused by handling, the coarse aggregates were allowed to air dry to a moisture content between 1% and 2%. Because concrete mix proportions are based on dry aggregate

weights, the measured moisture content also slightly affected the quantity of coarse aggregate batched for each mix.

Typically, adherent dust and clay particles are ignored when determining aggregate absorptions for concrete mix design. ASTM C127, for example, requires that coatings be washed from the surface of coarse aggregates before the absorption is measured. While ASTM C128 prescribes the cone test to determine the surface moisture of this fine material, a minimum sample of 1 kg of fines would need to be washed from the aggregate and dried before the test could be conducted - an undertaking that would not be practical. Clay coatings present additional problems since the plasticity of the material would affect its shear strength, the property on which the cone test is based. To overcome these difficulties, researchers have related the water absorption of soils to other common test parameters. For example, Sridharan and Nagaraj (1999) developed a relationship between the water-holding capacity of a soil and its liquid limit, as measured with the cone penetrometer method. Similarly, Pike (1992) cited research that correlated the methylene blue value to the liquid limit and water demand of the aggregate.

A combination of the methods described above was used to estimate the water absorptions of each aggregate coating. The relationship developed by Sridharan and Nagaraj (1999) was used to calculate the absorption of the highly plastic Sauk Cty fines, and the procedure prescribed in ASTM C128 was used to determine the absorption of the non-plastic Barron Cty fines. After measuring the methylene blue values of these materials, the absorptions of each coating were interpolated from the properties of Barron Cty and Sauk Cty fines, as suggested by Pike (1992). The results are listed in Table 3 and Table 4. Table 4 also shows the effective decrease in water-cement ratio caused by ignoring the coating absorptions in the mix design.

Table 3. Water Absorption Properties of Phase III Fines

Sample	Liquid Limit (%)	Water Absorption (%)	MBV (mg/g)
Barron Co.	Non-Plastic	1.7	1.7
Sauk Co.	78.0	72	14.3

The difference in water absorption of clay and non-clay particles is implied by the tabulated effects on the water-cement ratio. The water requirement of non-clay material is associated with the water that is used to fill the surface voids of an aggregate and is not available for cement hydration. However, the water absorption of clay particles includes water attracted to the surface of the particle by its net negative surface charge. While the layer of water closest to the particle is more viscous than ordinary water, the outer layer is similar to free water that adheres to the surface of non-clay particles and is assumed to be available for cement hydration. If the electrostatic attraction of water is accounted for by adding mix water to increase workability, as was done in Batch 10, the net water-cement ratio may be increased significantly. Generally, more water is required to reach an acceptable slump than is estimated from the absorption of the coating.

Table 4. Estimated Water Absorption of Aggregate Coatings

Batch	Coating Type	Water Absorption (%)	Net W/C Ratio
1	Carbonate	0.0	0.450
2	Dust/Clay	28.1	0.443
3	Carbonate/Clay	31.9	0.440
4	Carbonate	0.0	0.450
5	Dust/Clay	20.4	0.449
6	Carbonate/Clay	11.1	0.449
7	Dust	14.5	0.443
8	Dust	12.6	0.442
9	Clay	40.5	0.431*
10	Clay	55.5	0.467*

* based on assumptions concerning absorption and free water with clay coatings

4.4 Mix Design and Specimen Preparation in Phase III

Mix proportions were based on the WisDOT Grade A concrete mix design, as shown in Table 5 (WisDOT 1996). For each test batch, material quantities were determined to yield 3 ft³ of concrete with a net water-cement ratio of 0.45 and a target air content of 6.0 ± 1.0%. The following materials were donated by local suppliers and used throughout the study:

1. Type I cement from LaFarge Corp.
2. Coarse aggregate from Sources C, E, and H
3. Crushed limestone fine aggregate from Wingra Stone Co.
4. Saponified wood rosin air entrainer (Daravair 1400) from Grace Products

Table 5. Mix Design

Material	Batch Weights (lb/ft ³)	Batch Proportions
Cement	20.9	1
Coarse Aggregate	69.4	3.5
Fine Aggregate	46.3	2.25
Water (Net)	9.4	0.45

Concrete batches were machine mixed in a 3-ft³ drum mixer using the procedure specified in ASTM C192. Once mixed, the fresh concrete was tested for air content, unit weight, and slump. These properties were controlled during testing in order to limit the variability among the batches in the mix plan. Air content was measured with a Type B air meter and adjusted with the aggregate correction factor, following the standard procedure in ASTM C231. Before taking the measurement, the 0.25-ft³ bucket of the air meter was used to calculate the unit weight. Slump was determined according to ASTM C143 and used to estimate the differing water demands of the aggregate coatings.

After testing the fresh concrete, the following specimens were cast based on the methods described in ASTM C192.

1. Six 4-in. by 8-in. cylinders for compressive strength and permeability tests
2. Four 6-in. by 12-in. cylinders for tensile strength tests
3. Three 4-in. by 4-in. by 11-in. prisms for shrinkage tests
4. Five 3-in. by 4-in. by 15-in. prisms for freeze-thaw durability tests

Reusable metal forms were used to prepare the concrete prisms, while disposable plastic molds with plastic lids were used to prepare the concrete cylinders. As soon as the test specimens were cast, they were covered with wet burlap and a plastic sheet to retain moisture as the concrete hardened. Forms were removed after 1 day and cured in a wet room at a temperature of 74°F and a relative humidity of about 100% until the specimens were tested.

4.5 Hardened Concrete Tests in Phase III

Hardened concrete performance was assessed by measuring the strength, durability, tendency for cracking, and air void distribution of each concrete batch. The tests used to determine these properties are summarized in Table 6.

Table 6. Summary of Hardened Concrete Tests

Concrete Test	ASTM Standard	Tests per Batch	Duration of Curing
Compressive Strength	C39	4	28 days
Tensile Strength	C496	4	28 days
Drying Shrinkage	C490	3	14 days
Freeze-Thaw Durability	C666	3	28 days
Rapid Chloride Ion Penetrability	C1202	2	28 days
Petrographic Examination	C857	1	28 days
Air Void Analysis	C457	1	28 days

Compressive strengths were determined according to ASTM C39 using 4-in. by 8-in. concrete cylinders and a 28-day wet curing period. Before testing, the average diameter of each specimen was measured with a pi tape and used to calculate its cross-sectional area. Both ends of the cylinder were then capped with a sulfur compound to provide an even testing surface. During testing, specimens were loaded in axial compression at a constant rate of 1900 psi/min. In order to compare the strengths of batches with different air contents, the compressive strength of each specimen was adjusted to a nominal air content of 6.0% based on a compressive strength vs. air content relationship recommended by the American Concrete Institute (Popovics 1998).

Tensile strength was measured using the split-cylinder tension test described in ASTM C496. For each batch, four 6-in. by 12-in. cylinders were subjected to a compressive line load applied at a constant rate of 150 psi/min along the vertical diameter of the cylinder. Cardboard bearing strips were used to ensure that the load was transferred uniformly to the specimen surface. Since no empirical relationship was found between the splitting tensile strength and air content in published research, the test results were not adjusted to account for varying air contents amongst the concrete batches.

Drying shrinkage testing was conducted in general compliance with ASTM C490 using three concrete prisms with steel studs inserted at each end to provide a gage length of approximately 10.0 in. After 14 days of wet curing, the specimens were maintained in an environmental chamber at a temperature of 74°F and a relative humidity of 50%. Changes in length were recorded relative to an initial reading at various ages between 14 and 120 days using a length comparator gauge with a precision of 0.0001 in.

Freeze-thaw durability was assessed from the weight and stiffness degradation of three concrete specimens subjected to the environmental conditions specified in ASTM 666 Procedure A. The curing requirements set in the standard (14 days in lime water) were modified slightly (28 days of wet curing) in order for the concrete to reach a strength level more representative of field conditions. Samples were placed in a freezer following the curing period to prevent loss of moisture and control cement hydration up to the time of testing. Once testing was ready to commence, the specimens were thawed in air for 24 hours and soaked for another 24 hours in a 3% NaCl solution. For each test batch, three specimens were kept immersed in solution and cycled between 1°F and 50°F in a freeze-thaw chamber at an average rate of 4.5 cycles per day. The weight and fundamental transverse frequency were recorded for each specimen every 7 days, or roughly every 30 cycles. These measurements were used to calculate the relative changes in weight and dynamic modulus of elasticity with respect to the initial readings. The average changes for the three specimens at 200 and 400 cycles were interpolated from the data collected and used to make comparisons between test batches.

The rapid chloride ion penetrability test (ASTM 1202) was used as an indicator of the permeability of each concrete batch. For the test, two 2-in. thick specimens were cut from a 4-in. diameter cylinder with a diamond blade saw. Each of the specimens was conditioned prior to testing with an epoxy coating to seal pores on the outer surface and a vacuum desiccator to remove air from the sample. During vacuum conditioning, the internal pressure of the specimen was reduced to less than 1-mm Hg for 3 hours in a dry condition and an additional 1 hour under de-aerated water. The specimen was then allowed to soak in the water for 18 hours before the test was conducted. The test procedure consisted of

creating a voltaic cell by sandwiching the specimen between solutions of NaCl and NaOH and driving an electric current through the concrete. The total charge passed in 6 hours was related to the chloride ion penetrability of the specimen.

The hardened air void parameters were measured by a petrographic firm under contract with the University of Wisconsin-Madison. Samples were cut in the laboratory into 2-in. thick slices with a surface area of 12 in² and tested using the linear-transverse method prescribed in ASTM C457, Procedure A. In each test, the following air void parameters were measured: hardened air content, specific surface, void frequency, spacing factor, and paste-air ratio. As is frequently done in research, only one sample was analyzed for each batch in the mixing plan. However, three samples were tested for Batch 2 to estimate the variability of the air system in any one specimen.

Petrographic concrete thin-sections of specimens from Batches 2, 5, 8, and 10 were prepared by the University of Wisconsin-Madison Department of Geology and studied under a stereomicroscope following the guidelines specified in ASTM 856. Prior to preparing the specimens, samples were cut in the laboratory from concrete prisms with a cross-section of 3-in. by 4-in. Each specimen was then impregnated with an epoxy resin, ground to a thickness of 30 µm, and mounted on a 2-in. by 3-in. glass slide. Using a high-powered stereomicroscope, the specimens were examined at magnifications up to 400x. Specific characteristics that were examined included the quality of the aggregate-cement paste bond and the presence of microcracking in the cement paste. To confirm results observed with the stereomicroscope and to further investigate the interfacial zone in detail, additional specimens were sent to American Petrographic, Inc. who examined specimens under stereo-zoom and polarizing light microscopes up to a magnification of 1000x.

4.6 Aggregate Washing Survey

As part of the data analysis, two regional aggregate producers were interviewed to assess the potential economic impact of the test results on aggregate production. Participating producers were Wingra Stone, Inc. in Madison, WI and West Bend Sand & Gravel in West Bend, WI. Specific questions focused on the washing procedures and the marketability of suspect aggregates.

5. Aggregate Coating Characterization – Phase II Results

Samples collected from the 10 aggregate sources in Figure 2 were tested to determine the nature of the aggregate coatings prevalent in Wisconsin. X-ray diffraction was used to directly identify the mineralogy of each coating; the California Cleanness Test and methylene blue adsorption test were conducted to quantify the differences in mineralogy among the aggregates.

The minerals identified by x-ray diffraction are listed in Table 7 in order of intensity. In general, most of the coatings contained feldspar or carbonate material that was consistent with mineralogy of the aggregate itself. While dolomite and anorthite coatings were identified on the dolostone aggregates in southern Wisconsin, albite and amphibole coatings were identified on the granite aggregates in northern Wisconsin. These materials

can be classified as stone dust and should be distinguished from the clay material also found on the granite aggregates. The chlorite and illite clays identified in these aggregates are likely associated with the weathering of deposits in the northern portions of the state (D. Mickelson, personal communication).

Table 7. Phase II X-ray Diffraction Results

Source	Identified Minerals in Order of Intensity				
A - Washington Cty	Dolomite	Quartz	Anorthite		
B - Calumet Cty	Dolomite	Quartz	Anorthite		
C - Manitowoc Cty	Dolomite	Quartz			
D - Dane Cty	Dolomite	Quartz	Anorthite		
E - Marathon Cty	Quartz	Albite	Chlorite	Illite	Amphibole
F - Eau Claire Cty	Quartz	Albite	Chlorite	Amphibole	
G - Eau Claire Cty	Quartz	Albite	Chlorite	Illite	Amphibole
H - Dodge Cty	Dolomite	Quartz	Anorthite	Chlorite	Amphibole
I - Oneida Cty	Quartz	Albite	Chlorite	Amphibole	
J - Oneida Cty	Quartz	Albite	Chlorite	Amphibole	

The cleanness values measured for each aggregate are plotted in Figure 3. These values measure the extent of the coating and are related to the clay content of the aggregate. As shown in Figure 3, most of the values ranged between 90 and 95, which is well above the California specification limit of 75. The lowest cleanness values, 89 and 85, were measured for the aggregate from Source E and Source H, respectively. This follows from the larger quantity of adherent material that was observed on these aggregates and the x-ray diffraction results, which identified small amounts of clay material in each coating. Although clay minerals were also found in the Source F and G aggregate coatings, the quantity of clay was too small to influence the cleanness value.

The quantity and activity of clay in each coating was assessed with the methylene blue value. Since the adsorption of methylene blue dye is related to the specific surface and cation exchange capacity of the minerals contained in a sample, the value can be used to distinguish between clay and non-clay coatings. The results shown in Figure 4 confirm the differences in mineralogy between the coatings found in the northern and southern parts of the state. While the methylene blue values of the dolomite coatings were less than 3 mg/g, the methylene blue values of the feldspar coatings were greater than 5 mg/g. The exception was the coating on the unwashed aggregate from Source H, which had a methylene blue value of 9.3 mg/g and consisted of both dolomite and clay. The higher values shown in Figure 4 are associated with the concentrations of the chlorite and illite minerals that were identified in many of the samples.

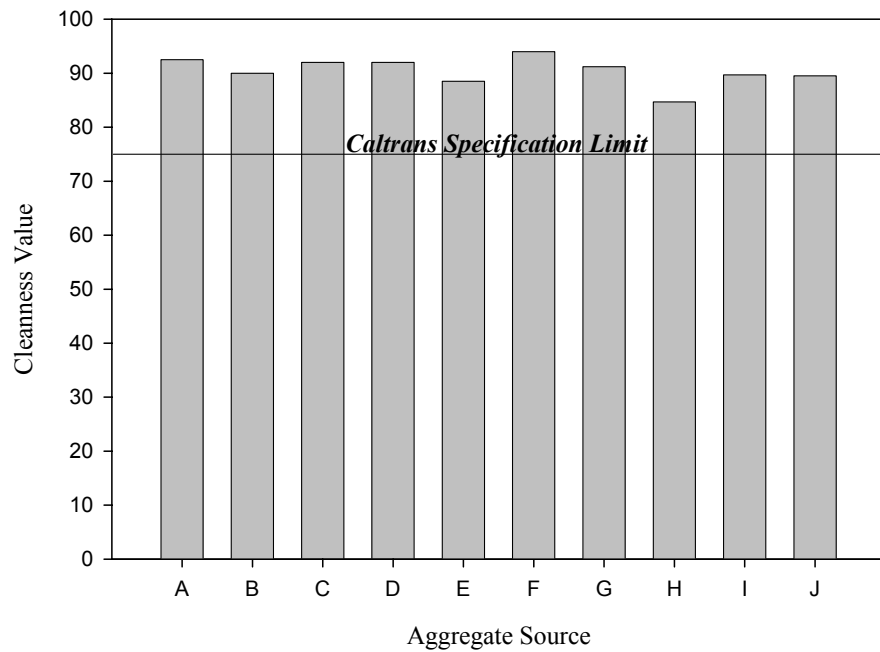


Figure 3. Results of California Cleanness Test

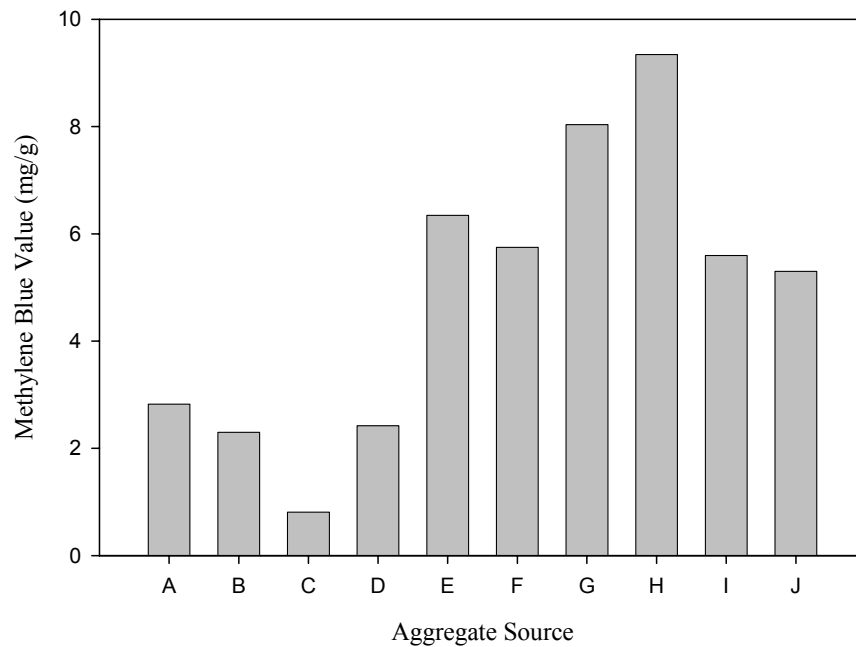
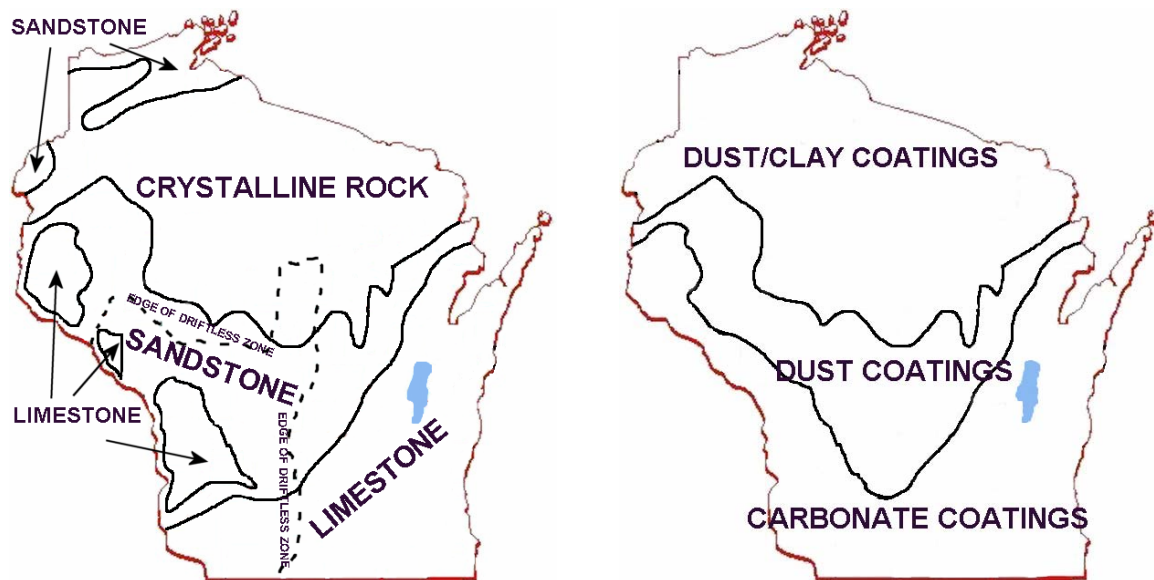


Figure 4. Phase II Results of Methylene Blue Adsorption Test

The results of the aggregate coating tests indicated that coatings consist largely of particles that have the same mineralogy as the aggregate deposit. The coatings in southern Wisconsin contain mostly carbonate minerals, and the coatings in northern Wisconsin

contain major amounts of feldspar minerals and minor amounts of clay. Essentially, these minerals are the basic rock-forming minerals of the aggregate types found in Wisconsin. Dolomite, quartz, and anorthite are important constituents of the dolostone and quartzite deposits in the southern part of the state; albite, quartz, and amphibole are important constituents of the igneous deposits in the northern part of the state. The clay minerals are most likely associated with the slow disintegration of the igneous rocks. Since the mineralogy of the coatings appears to be closely related to the type of aggregate, the map of the major aggregates produced in Wisconsin shown in Figure 5 was modified to show the expected mineralogy of aggregate coatings in the state.



**Figure 5. Aggregate and Coating Types in Wisconsin
(after Hotchkiss and Steidmann 1914)**

Following the general characterization of Wisconsin aggregate coatings, a representative subset was selected to study the effects of aggregate coatings on concrete performance in Phase III. The coating types and aggregate sources selected are described below. The p200 percentage, cleanness values, methylene blue values, and modified methylene blue values measured for these aggregate coatings are tabulated in Table 8 .

Table 8. Phase III Results of Coating Characterization Tests

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	MMBV (mg/g)
Source C Aggregate - Manitowoc Cty					
1	Coated - Field	0.3	94	0.8	0.002
4	Washed - Lab	0.1	97	0.8	0.001
Source E Aggregate - Marathon Cty					
2	Coated - Field	0.7	85	6.4	0.05
5A	Washed - Lab	0.2	97	5.1	0.009
7	Coated - Lab ¹	1.4	82	4.0	0.05
8	Coated - Lab ¹	1.9	79	3.7	0.07
9	Coated - Lab ²	1.4	23	8.7	0.12
10	Coated - Lab ²	1.3	14	11.4	0.15
Source H Aggregate - Dodge Cty					
3	Coated - Field	0.9	86	6.0	0.06
6	Washed - Lab	0.2	97	3.4	0.006

¹ Coatings manufactured with dust fines from Barron Cty

² Coatings manufactured with clay fines from Sauk Cty

Source C Aggregate – Manitowoc Cty

The low p200 percentage and high cleanness value of the Source C aggregate indicate that only a small amount of material adhered to the aggregate surface. Since the p200 percentage was 0.3%, which is significantly lower than the WisDOT specification limit of 1.5%, it is unlikely that the coating will cause any noticeable changes in the concrete. The low methylene blue value suggests that the coating is predominantly dolomite and provides further evidence that the coating is innocuous. Because of the cleanliness of the aggregate, washing did not significantly change the amount or clay content of the adherent material.

Source E Aggregate – Marathon Cty

The cleanness value and methylene blue value of the coated aggregate imply that the Source E coating contains moderate amounts of clay material. However, it was initially uncertain if the coating is harmful because the cleanliness parameters were within California specification requirements. Although minor amounts of illite and chlorite were identified in the coating in Phase II, the cleanness value of 85 and the methylene blue value of 6.4 mg/g did not suggest any deleterious effects to be likely. (Recall the French specifications limit MBV to 10 mg/g.) To increase the extent and clay content of the coating, dust fines from

Barron Cty and clay fines from Sauk Cty were added to the aggregate in Batches 7-10. The mineralogy of each sample of fines, determined by x-ray diffraction, is shown in Table 9.

Table 9. Phase III X-Ray Diffraction Results for Added Fines

Sample	Identified Minerals in Order of Intensity				
Barron Cty	Quartz	Albite	Anorthite	Labradorite	Microcline
Sauk Cty	Quartz	Muscovite	Anorthite	Chlorite-Vermiculite-Montmorillonite	

The feldspar minerals identified in the Barron Cty fines and the clay minerals identified in the Sauk Cty fines modified the original dust/clay coating into a dust coating and a clay coating, respectively. The nature of these coatings is reflected in the results of the characterization tests tabulated for Batches 7-10 and shown in Section 6. The most significant changes in the test parameters were associated with the additions of clay fines in Batch 9 and Batch 10. In particular, the cleanness values of both aggregates were well below the California specification limit, which proves the test sensitivity to clay particles. Similarly, the modified methylene blue values (~0.15 mg/g) were considerably higher than the value measured for the coated aggregate in Batch 2. According to Ahn and Fowler (2000), fine aggregate with a modified methylene blue value of 0.30 mg/g can significantly increase the water demand of the aggregate. However, the contribution of the coarse aggregate was not included in this assessment, and the 0.15 mg/g measurement in this research would likely lead to increased water demand when combined with the water demand associated with the modified methylene blue value of the fine aggregate. Considering that concrete contains more coarse aggregate than fine aggregate, the clay contents of these aggregates may be high enough to frustrate the control of mixing water. Unlike the additions of clay fines, the additions of dust fines in Batches 7 and 8 did not significantly affect the test parameters. Both the cleanness value and modified methylene blue value were similar to the values measured for Batch 2. Interestingly, the cleanness value of the Batch 8 aggregate was within the California specification even though the p200 percentage was greater than the WisDOT limit, but the opposite was true for the aggregates used in Batches 9 and 10.

Source H Aggregate – Dodge Cty

Both the p200 percentage and methylene blue value of the coated Source H aggregate were high because the aggregate was not washed on-site before it was sampled. Despite the severity of the coating, the California cleanliness rating of the aggregate washed in the lab was similar to the cleanliness of the other washed aggregates. The significant decrease in methylene blue value after washing was most likely associated with the removal of chlorite minerals during the washing procedure. Incidentally, the resulting methylene blue value (3.4 mg/g) closely matches the values measured for the dolomite coatings of Sources A, B, and D in Phase II.

6. Concrete Test Results – Phase III

6.1 Source C Aggregate – Manitowoc Cty - Dolostone with Carbonate Coating

The average hardened concrete properties for the concrete batches mixed with the Source C aggregate are shown in Tables 10 and 11 along the characterization parameters determined from the aggregate coating tests. Observations inferred from the coated aggregate vs. washed aggregate comparisons are listed below:

- The same slump was measured for the concrete batch mixed with the coated aggregate and the batch mixed with the washed aggregate. This implies that the carbonate coating did not have a water absorption that would impact general workability.
- Both the average compressive and tensile strength measured for the coated aggregate batch were higher (1% and 17%, respectively) than the strengths measured for the washed aggregate batch. Based on an ANOVA at a 5% level of significance, only the difference in tensile strength could be distinguished statistically. The increased tensile strength of the coated aggregate batch suggests that carbonate coatings can improve the strength of certain concrete mixtures.
- The 56-day drying shrinkage associated with the coated aggregate was 3% lower than the shrinkage associated with the washed aggregate. This result supports the results of the slump test, which showed that the difference in water demands between the two batches was negligible.
- The freeze-thaw durability of the coated aggregate batch was essentially the same as the washed aggregate batch. While the average stiffness degradation associated with the coated aggregate was 5.0% higher than the stiffness degradation associated with the washed aggregate at 200 cycles, only a 0.3% difference was noted at 400 cycles. The increased stiffness degradation of the coated aggregate batch may be traced to a small crack that expanded to expose a coarse aggregate in the interior of one of the specimens. For both concrete batches, the weight degradation was less than 1% at 400 cycles.
- The chloride ion penetrability of the coated aggregate batch was 22% higher than the chloride ion penetrability of the washed aggregate batch. However, this difference could not be distinguished statistically with only two specimens tested per batch. The result was likely caused by the variability of the test procedure (required ASTM C1212 precision = 35%) rather than the aggregate coating since the freeze-thaw tests did not show any differences in durability.

The results indicate that the carbonate coating on the aggregate was largely innocuous. For the majority of the strength and durability parameters, the coated aggregate outperformed the washed aggregate. Despite the apparent difference between these batches, only the change in tensile strength could be distinguished statistically. Although large differences in concrete performance were not expected, the apparent beneficial effect of the carbonate coating was surprising since the amount of adherent material (0.26%) was well within the WisDOT p200 specification (1.5%) and the clay content, as measured by the methylene blue value (0.78 mg/g), was low. It is evident that additional washing of such aggregates is not necessary.

Table 10. Strength and Shrinkage Results for Source C (Manitowoc Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Compressive Strength (psi)	Tensile Strength (psi)	56-day Shrinkage (%)
1	Coated – Field	0.3	94	0.8	4500	410	0.038
4	Washed - Lab	0.1	97	0.8	4450	345	0.039

Table 11. Durability Results for Source C (Manitowoc Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Durability (200 Cycles)		Durability (400 Cycles)		RCP (Coulombs)
					Stiffness (%)	Weight (%)	Stiffness (%)	Weight (%)	
1	Coated – Field	0.3	94	0.8	84.5	99.7	84.0	99.1	4430
4	Washed - Lab	0.1	97	0.8	88.8	100.0	84.1	99.4	3540

6.2 Source E Aggregate – Marathon Cty - Granite with Dust/Clay Coatings

The average hardened concrete results and aggregate coating parameters for the Source E aggregate batches are listed in Tables 12 and 13. As indicated by the coating characterization tests, the types of coatings existing or applied to the aggregate included dust, clay, and dust/clay coatings. The variation in the quantity and mineralogy of these coatings permitted a more in-depth coated vs. washed aggregate comparison than was possible for the other aggregate coatings (see Section 7).

- As the clay content of the coating increased, the slumps measured for the coated aggregate batches ($\frac{1}{4}$ in. to $1\frac{1}{2}$ in.) decreased steadily with respect to the washed aggregate batch ($2\frac{1}{2}$ in.). The most dramatic change was observed for the manufactured clay coating tested in Batch 9. After a $\frac{1}{4}$ -in. slump was measured for this batch, an additional 9% of mixing water was required in Batch 10 to maintain the same workability as the washed aggregate batch. In contrast, the slumps measured for Batch 7 and Batch 8 were comparable to the slump of the field coated aggregate batch even though considerable amounts of dust fines were added. Since a slump between 1 and $2\frac{1}{2}$ in. is required for slip-formed concrete pavements, it is doubtful whether these dust coatings would have been detected in the field.
- The differences in compressive strengths between the coated and washed aggregate batches generally agree with the strength losses predicted by Goldbeck (1932) and Pike (1992). In Batch 8, a 1.7% increase in adherent dust fines produced a 2.2% decrease in strength relative to the washed aggregate batch. In Batch 9 and Batch 10, a 1% addition of dust, montmorillonite, and kaolinite fines decreased the compressive strength by 4.7%. Although an ANOVA performed on the compressive strength results indicated that these differences approached the threshold of statistical significance, the 5% changes in strength would not likely be of practical importance in the field.
- The relative changes in tensile strength, unlike compressive strength, do not appear to be related to the extent of the coating. For example, a 6% increase and 1% decrease in tensile strength were recorded for Batch 2 and Batch 8, respectively, despite significant amounts of p200 material on the aggregate. A larger strength reduction was anticipated for Batch 8 since the p200 percentage exceeded the 1.5% limit in the WisDOT specifications. The high tensile strength of Batch 9 can be traced to low air content (3.7%). Like the changes in compressive strength, the differences are not likely to be noticed in the field.
- The average shrinkage percentages consistently increased as the severity of the coating increased. According to the data analysis, the coated aggregate batches can be divided into two groups: (1) Batch 2, 7, 8, and 9 with an average shrinkage of about 0.045% and (2) Batch 10 with an average shrinkage greater than 0.055%. The 56-day shrinkage of Batch 10 was about 65% greater than the shrinkage of the washed aggregate batch. This difference may account for unexpected cracking in pavements mixed with aggregates containing clay coatings.
- More pronounced changes in durability were associated with the clay coatings in Batch 9 and Batch 10 than the dust coatings in Batch 7 and Batch 8. While the initial weight and stiffness of the concrete was retained after 400 cycles in the specimens containing the dust-coated aggregates, considerable scaling and stiffness degradation were observed in the specimens containing the clay-coated aggregates. Although the difference in durability among the batches could not be distinguished at 200 cycles, the statistical analysis detected significant differences in the clay coating batches at

400 cycles. The largest differences in durability relative to the washed aggregate batch were measured for Batch 10, which suffered a 4.5% reduction in stiffness and a 4% reduction in weight after 400 cycles. It is likely that this increased deterioration was caused by the additional water used to increase slump during mixing.

- Like the freeze-thaw durability test, the chloride ion penetrability results show that dust and clay coatings only affect chloride ion resistance if the water demand of the adherent material is important. In the batches for which the absorptions of the coating were ignored, the total charge passed did not vary significantly from the washed aggregate batches. However, the increased water content of Batch 10, however, coincided with a 39% increase in the total charge passed relative to the washed aggregate batches. Based on the ANOVA and Tukey multiple comparison tests, the difference is statistically significant.

The results suggest that clay coatings have stronger and more deleterious effects on concrete performance than dust coatings. As the p200 percentage of the aggregates approached the WisDOT limit, the aggregates with 1.4% and 1.3% clay coatings produced significant changes in shrinkage and durability but the aggregates with 1.4% and 1.9% dust coatings did not significantly affect these properties. The distinction between these coating types is likely associated with their water absorption. The results of Batch 10 show that when water is added during mixing to correct for this water demand, shrinkage can increase by 65% and strength and freeze-thaw durability can decrease by 5%.

Table 12. Strength and Shrinkage Results for Source E (Marathon Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Compressive Strength (psi)	Tensile Strength (psi)	56-day Shrinkage (%)
2	Coated – Field	0.7	85	6.4	4790	430	0.043
5	Washed – Lab	0.2	97	5.1	4820	410	0.034
7	Coated – Lab	1.4	82	4.0	4630	380	0.042
8	Coated – Lab	1.9	79	3.7	4710	395	0.046
9	Coated – Lab	1.4	23	8.7	4600	470	0.046
10	Coated - Lab	1.3	14	11.4	4600	365	0.056

Table 13. Durability Results for Source E (Marathon Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Durability (200 Cycles)		Durability (400 Cycles)		RCP (Coulombs)
					Stiffness (%)	Weight (%)	Stiffness (%)	Weight (%)	
2	Coated – Field	0.7	85	6.4	99.2	100.1	99.3	98.7	3330
5	Washed – Lab	0.2	97	5.1	101.1	100.0	100.0	99.0	3390
7	Coated – Lab	1.4	82	4.0	100.9	99.9	102.2	99.4	3710
8	Coated – Lab	1.9	79	3.7	100.5	99.8	101.8	99.4	3250
9	Coated – Lab	1.4	23	8.7	100.2	99.4	98.1	96.6	3800
10	Coated - Lab	1.3	14	11.4	98.7	99.3	95.6	96.3	5010

6.3 Source H Aggregate – Dodge Cty - Dolostone with Carbonate/Clay Coating

The average hardened concrete properties for the concrete batches with the Source H aggregate are shown in Tables 14 and 15 along the characterization parameters determined from the aggregate coating tests. The comparisons made between the coated aggregate and washed aggregate batches are described below for each property tested:

- Similar to the changes in slump attributed to the Source E aggregate coatings, the carbonate/clay coating on the Source H aggregate decreased the slump of the washed aggregate batch from 3 in. to 1¾ in. The probable cause of this difference was the water absorption of the coating, which was ignored in the mix design but decreased the estimated net water-cement ratio by 0.01.
- Slight increases in compressive (5.4%) and tensile strength (9.2%) were observed for the concrete batch mixed with the coated aggregate and the concrete batch mixed with the washed aggregate. These differences are likely a result of the estimated decrease in water-cement ratio.
- Although the carbonate/clay coating appeared to increase the water demand of the concrete in the slump test, it did not have the same effect on drying shrinkage. The 56-day shrinkage of the coated aggregate batch was 5% lower than the shrinkage of the washed aggregate batch.
- For both the coated aggregate and washed aggregate batches, the stiffness and weight degradation after 400 cycles was 25-30% and 2-3%, respectively. Although more scaling and popouts were observed in the coated aggregate specimens, cracking appeared to accelerate the deterioration of two of the washed aggregate specimens. At approximately 200 cycles, this deterioration fractured a large piece of concrete at one of these cracks. Since this fracture occurred through the aggregates, the failure was likely caused by the frost susceptibility of the aggregate rather than a weakness of the interfacial zone.
- The chloride ion penetrability associated with the coating aggregate was 27% higher than the chloride ion penetrability associated with the washed aggregate. As with the other aggregates that were tested, this relative difference was potentially caused by variability of the rapid chloride ion penetrability test rather than the aggregate coating.

The results seem to be a balance between the positive effects observed for the carbonate coating on the Source C aggregate and the dust/clay coatings on the Source E aggregate. Although the clay minerals in the coating appeared to increase the water demand of the concrete batches like the dust/clay coatings tested with the Source E aggregate, the changes in strength and durability were more like the changes observed for the Source C aggregates. Due to these opposing effects, none of the coated aggregate vs. washed aggregate differences reached statistical significance. This implies that aggregates with limited amounts of clay coatings are not significantly detrimental for concrete pavement applications.

Table 14. Strength and Shrinkage Results for Source H (Dodge Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Compressive Strength (psi)	Tensile Strength (psi)	56-day Shrinkage (%)
3	Coated – Field	0.9	86	6.0	4780	400	0.038
6	Washed - Lab	0.2	97	3.4	4530	365	0.040

Table 15. Durability Results for Source H (Dodge Cty) Aggregate Batches

Batch	Concrete Series	p200 (%)	Cleanness Value	MBV (mg/g)	Durability (200 Cycles)		Durability (400 Cycles)		RCP (Coulombs)
					Stiffness (%)	Weight (%)	Stiffness (%)	Weight (%)	
3	Coated – Field	0.9	86	6.0	86.2	99.3	76.3	98.1	4560
6	Washed - Lab	0.2	97	3.4	80.6	99.2	72.4	97.2	3460

7. Significance of Aggregate Coatings

7.1 Correlation of Test Parameters

Based on the comparisons described in Section 6, carbonate coatings slightly increase concrete strength and durability whereas dust/clay coatings tend to decrease these properties. To isolate the characteristics that make a coating deleterious and identify tests that can be used to monitor them in the field, the parameters of the aggregate coating tests were correlated with the properties of the hardened concrete tests. However, only the Source E aggregate tests were used in the analysis because of the additional data points provided by the concrete batches mixed with the manufactured dust and clay coatings. The correlations of the test parameters are shown in Table 16.

Table 16. Correlation of Source E Aggregate Coating Parameters on Concrete Properties

Parameter	Concrete Strength		Concrete Durability			
	Compressive Strength	Tensile Strength	Drying Shrinkage	Stiffness Durability	Weight Durability	Chloride Penetration
p200 %	-0.68	-0.51	0.62	-0.14	-0.30	0.17
Cleanness Value	0.81	0.72	-0.82	0.72	0.96	-0.81
MBV	-0.52	-0.42	0.71	-0.83	-0.85	0.85
MMBV	-0.82	-0.68	0.93	-0.76	-0.89	0.80

The tabulated correlation coefficients indicate that the p200 percentage is an imperfect predictor of the deleterious nature of aggregate coatings. As shown in the table, there is only a weak relationship between the p200 percentage and concrete strength, and the relationship between the p200 percentage and concrete durability is even weaker. Based on these differences, it is evident that the effect of aggregate coatings is not solely dependent on the p200 percentage of the aggregate. The result is best explained by the behavior of the dust coatings and clay coatings created with the Barron Cty and Sauk Cty fines. The manufactured dust coatings were largely innocuous as the adherent dust caused only small changes in concrete strength and durability even when the extent of the coating exceeded 1.5% of the aggregate weight. On the other hand, the coatings containing a similar percentage of clay material were more deleterious as the addition of the clay material resulted in significant changes in concrete performance. The inadequacy of the p200 test to monitor aggregate coatings is even more apparent when the properties of the Source C and Source H concrete batches are considered. For each of these aggregates, increases in the amount of p200 material were associated with increases in both compressive and tensile strength.

The impact of aggregate coatings appears to be closely associated with the mineralogy of the adherent material as well as the extent of the coating. In this study, the mineralogy of the p200 material was measured with the methylene blue value. As discussed previously, this parameter is closely related to the absorptive properties of clay material and is often used to detect the presence of clay minerals. Compared to the p200 percentage, the methylene blue value had a much stronger correlation with the properties

related to concrete durability. However, like the p200 percentage, the parameter is only weakly related to concrete strength. The distinction between these correlations results from the different properties of the adherent materials. Clay coatings are able to absorb much more water than either dust or carbonate coatings due to their unique internal structure. As a result, water that is expelled during cycles of freezing and thawing durability can increase the critical saturation of the cement paste and impair durability (Newlon and Mitchell 1994).

Although mineralogy is an important indicator of deleterious coatings, the extent of the coating must also be considered. As shown in Table 16, the effects of aggregate coatings are best predicted by the California Cleanness Value and the modified methylene blue value, which is related to both the mineralogy and total percentage of the p200 material. Although the correlations for these tests were stronger than the other characterization tests, they are not perfect predictors of the effects of aggregate coatings. Because the correlations ranged between 0.68 and 0.96, it appears that several other unknown parameters, like strength of adherence, may also influence performance.

The carbonate coatings on the Source C and Source H aggregates appeared to improve concrete strength, which supports the claim made in earlier reports that some coatings can improve concrete performance (Schmitt 1990). Based on the evaluation of the carbonate/clay coating on the Source H aggregate, the innocuous behavior of the carbonate fines may even counteract the deleterious behavior of clay fines. Despite a significantly lower cleanness value and higher modified methylene value, the aggregate and coating sampled from Source H outperformed the washed aggregate. The result appears to discount the use of the California Cleanness Test and methylene blue adsorption test to monitor coatings with large amounts of carbonate material. However, additional testing of more extensive carbonate and clay coatings is required before this can be concluded.

7.2 Petrographic Examination of the Aggregate-Paste Interface

The washed vs. coated aggregate comparisons described in the previous sections, support the theory that clay coatings behave differently than dust coatings because more pronounced changes in strength and durability were associated with the manufactured clay coatings studied in Batches 9 and 10 than with the manufactured dust coatings studied in Batches 7 and 8. Based on previous research, it was theorized that the observed decreases in tensile strength and durability were produced by the water absorption and adherence of the clay fines. According to St. John et al. (1998), the high absorption of tightly adhering clay material can increase the concentration of water at the aggregate-cement paste interface, causing the cement paste to separate from the aggregate and calcium hydroxide to crystallize in the spaces that are created. This effect often produces an aureole around the aggregate that can be observed during a petrographic examination.

In order to study the interfacial zone in detail, thin-sections were prepared for several of the Source E concrete batches (Batches 2, 5, 8 and 10) and examined under a stereomicroscope at magnifications up to 400x. Photomicrographs of the thin-sections are provided in Appendix H. Analogous to the washed vs. coated aggregate comparisons used to analyze the hardened concrete properties, comparisons of the Batch 5 observations and the Batch 2, 8, and 10 observations were used to investigate the apparent effects of the dust/clay coatings. The results of the petrographic examination did not provide any clear

evidence of air voids, microcracks, or other signs of distress at the aggregate-cement paste interface in any of the samples.

Samples for were sent to American Petrographic, Inc. (API) to provide independent assessment of the samples with the use of higher magnification. Samples from Source E batches 5 (washed), 2 (0.7% field coated), 8 (1.9% lab coated dust fines) and 10 (1.3% lab coated clay fines) were sent for petrographic examination. Specifically API was asked to assess whether the aggregate fines were dispersed or observed to be adhering to the aggregate particles and whether there were any discernable differences in the paste-aggregate interfacial zone when comparing one specimen to another. They followed ASTM C856 using a stereo-zoom microscope and a polarizing light microscope. There findings are summarized in Table 17.

Table 17. Observations from Petrographic Examination by American Petrographic, Inc.

Batch	Concrete Series	p200 (%)	Cleaness Value	MBV (mg/g)	API Observations
2	Coated – Field	0.7	85	6.4	“unremarkable”, darker colored, denser paste in several concave coarse aggregate notches. Small amount of air void concentration around paste-aggregate boundaries (see Fig. 6).
5	Washed – Lab	0.2	97	5.1	Mottled paste coloration on microscopic scale. Darker colored, denser paste in several concave coarse aggregate notches. Few rock fines observed. CaOH concentrated along paste-aggregate boundaries. No apparent concentration of air voids at paste-aggregate boundaries (see Fig. 6).
8	Coated – Lab	1.9	79	3.7	Similar in observed rock fines to Batch 2. Darker colored, denser paste in several concave coarse aggregate notches otherwise paste color was consistent. CaOH well distributed throughout paste.
10	Coated – Lab	1.3	14	11.4	Paste color lighter with hint of orange. No individual clay particles discernable. Concentrations of orange clay evident in concave coarse aggregate notches. Air voids had a propensity to concentrate along the paste-coarse aggregate boundaries (see Fig. 7).

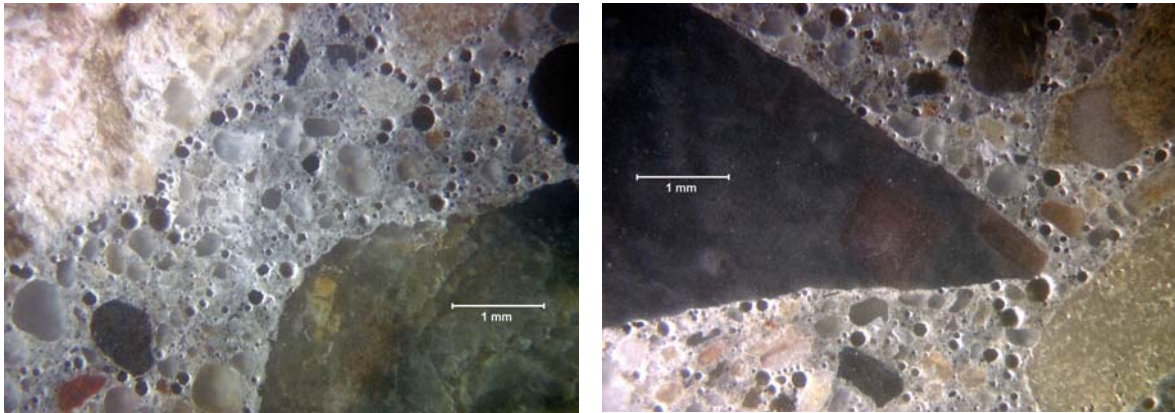


Figure 6. Micrographs of paste-aggregate interface in specimens from Batch 2 and Batch 5 respectively.

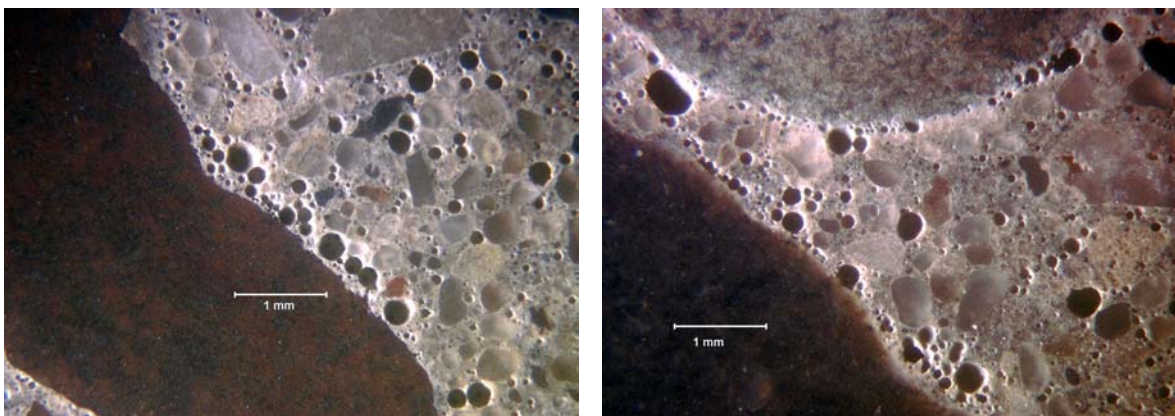


Figure 7. Micrographs of paste-aggregate interface in specimen from Batch 10 showing concentration of air voids.

7.3 Survey of Aggregate Producers

Washing is now an integral part of the aggregate producing operation in Wisconsin. Existing equipment would not be abandoned if washing was determined to be unnecessary, but in the long range, new equipment purchases would be tailored to match DOT requirements. There are also differences in limestone crushing operations versus pit run sorting operations. Although the Dodge County aggregate (aggregate H) was not washed and performed satisfactorily, the scope of research did not evaluate the impact of absolutely no washing on a state-wide basis nor at what point excessive amounts of coatings would impact concrete performance.

Although all of the samples, except for the Source H aggregate, were collected after the stone was washed and graded, coatings were visible on the surface of each aggregate. It is likely that most of the dust coatings were generated during the processing, crushing, and handling of the aggregates after they were washed. On the other hand, the clay coatings were created by weathering processes and remained attached to the aggregate after washing. Since the coatings consisted predominantly of stone dust and only partially of clay, the measured cleanness values were well within the California specification limit. As a result, the clay contents of the sampled coatings appeared to be small and unlikely to affect performance.

Because the results of the concrete tests suggest that coatings adhering to field-washed aggregates have only minor effects on concrete strength and durability, it appears that current washing procedures are adequate and not responsible for perceived aggregate coating problems. However, the results also indicate that aggregates that contain excessive clay coatings, as examined in Batches 9 and 10, are more deleterious than aggregates that contain excessive dust coatings, as examined in Batches 7 and 8. These differences imply that p200 specifications and washing methods, for coarse aggregates could potentially be relaxed if the fines consist predominantly of dust fines rather than clay fines. Regional sand and gravel companies were surveyed to estimate the benefit of such processing changes to aggregate producers. The results are listed below:

- Andy Balch of Wingra Stone, Inc., suggests that a change in the WisDOT specification could affect the economy of aggregate washing. When coarse aggregate containing dust fines are processed, less intensive washing would be required than if coarse aggregates containing clay fines are produced. Consequently, the washing procedure would require take less time and be less labor intensive.
- According to David Johnson of West Bend Sand & Gravel, Inc., knowledge of the difference between dust and clay coating could affect the production costs by influencing the equipment required to process aggregates in newly developed deposits. For example, equipment that uses less water pressure during washing would result in a cost benefit to the aggregate producer in areas where only dust coatings are encountered. For smaller and older plants, however, the effects on water usage and sediment collection would be minor. An increase in the allowable p200 percentage for dust coated aggregates could also benefit the producer by opening suspect areas in an aggregate pit that would otherwise not be developed; the total volume of aggregate produced would likely not be affected.

Such costs with regards to state-wide impact were not possible to quantify within the scope of this study. The impact would likely be different for each aggregate producer. The

producers surveyed conveyed the sense that while less restrictive specifications would be welcome, there would not be significant changes to their current operations or the cost of those operations. The research team did not feel additional attention to this topic was warranted.

8. Summary and Conclusions

The aggregate coatings found in Wisconsin can be grouped into three basic types: dust coatings, clay coatings, and carbonate coatings. The coatings in northern Wisconsin are predominantly a combination of dust and clay material, and the coatings in southern Wisconsin are predominantly carbonate coatings. Although the nature of these coatings has traditionally been associated with the amount of material adhering to the aggregate surface, this research shows that the coatings that adhere to washed aggregates in the field have only minor effects on concrete strength and durability except in select situations.

In this study, the importance of p200 limit specifications was evaluated from the three groups of coarse aggregates included in the mixing plan: (1) washed aggregates prepared in the lab with p200 percentages less than 0.2%, (2) coated aggregates sampled in the field with p200 percentages ranging from 0.2% to 1.0%, and (3) coated aggregates created in the lab with p200 percentages approaching or exceeding the WisDOT p200 limit. Dust and carbonate coatings up to amounts exceeding the 1.5% p200 limit did not cause any deleterious impact on concrete when the water content of the batch was unadjusted for the moisture adsorption of the coating. Even if field water additions were made to maintain workability it is unlikely such additions would significantly alter the net water-cement ratio.

The test results of the aggregate coatings manufactured in the lab indicate that aggregates with clay coatings and a p200 percentage near 1.5% can potentially produce noticeable changes in slump and durability. Drying shrinkage increased by approximately 65% when extensive clay coatings were present. Impacts on workability were significant and could prompt field additions of water that may negatively impact other concrete properties. Despite the fact that these effects may be mitigated by vigorously rewashing the aggregate until the adherent clay is removed, the resulting increases in concrete strength (5%) and durability (3%) do not appear to warrant additional aggregate washing.

Survey of the state aggregates did not reveal aggregates with significant harmful clay-type coatings. Clay coatings can be a problem but we did not find any naturally occurring aggregates with coatings that could be considered injurious. However, the study sample was small and the potential for deleterious coatings in field aggregates to exist could not be ruled out.

9. Recommendations

In most situations in Wisconsin, concrete is a sufficiently robust material in production and in performance such that it can tolerate minor aggregate coatings. In most situations, this tolerable level of innocuous coating probably exceeds the state limit of 1.5% p200. Although existing specifications imply that the extent of aggregate coatings determines their effects on concrete performance, the test results show that mineralogy is a

more important indicator of deleterious and innocuous coatings. Currently, coatings are controlled in the field by limiting the amount of p200 material on the aggregate. However, the calculated correlations between the test parameters measured for the dust/clay coatings and the corresponding hardened concrete properties indicate that the California Cleanness Test is a better predictor of concrete strength and durability. During the study, aggregates containing significant clay coatings passed the WisDOT p200 requirement but failed the California Cleanness Value specification. Because the cleanness test measures the extent of the coating while distinguishing clay coatings from dust or carbonate coatings, it is more closely related to the mechanisms that impair concrete performance. As a result, it is recommended that WisDOT require California Test 227 as a replacement for the P200 limit of 1.5% or, as a less burdensome alternative, whenever aggregate coatings are suspected of influencing strength or durability during concrete construction. No changes to current aggregate washing procedures are recommended.

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CORRESPONDANTS

Dr. David Mickelson. Professor of Geology and Geophysics. University of Wisconsin-Madison.

Appendix A. California Test 227

DEPARTMENT OF TRANSPORTATION
ENGINEERING SERVICE CENTER
Transportation Laboratory
5900 Folsom Boulevard
Sacramento, California 95819-4612



METHOD OF TEST FOR EVALUATING CLEANNESS OF COARSE AGGREGATE

CAUTION: Prior to handling test materials, performing equipment setups, and/or conducting this method, testers are required to read "**SAFETY AND HEALTH**" in Section I of this method. It is the responsibility of the user of this method to consult and use departmental safety and health practices and determine the applicability of regulatory limitations before any testing is performed.

A. SCOPE

The cleanness test provides an indication of the relative proportions of clay-sized material clinging to coarse aggregates or screenings.

B. APPARATUS

The following equipment is required to perform this test. Detailed descriptions and specifications are included as necessary to ensure standardization.

Items bearing a Business Management (OBM) or Office of Purchasing and Warehousing (OPW) catalog number are available to California State agencies from the Department of Transportation, Office of Purchasing and Warehousing. Detailed plans are available for those items bearing a Transportation Laboratory (TL) drawing number.

1. Agitator (Figure 1): A mechanical device designed to hold the wash vessel in an upright position while subjecting it to a lateral reciprocating motion at a rate of 285 ± 10 complete cycles per minute. The reciprocating motion shall be produced by means of an eccentric located in the base of the carrier, and the length of the stroke shall be 44.4 ± 0.6 mm. The clearance between the cam and follower of the

eccentric shall be between 0.025 mm and 0.102 mm. Other types of agitators may be used provided the length of time and other factors are adjusted to produce the same results as those obtained using the agitator described above.

2. Wash vessel: A flat-bottom, straight-sided, cylindrical vessel conforming to the specifications and dimensions shown in Figure 2.
3. Washing pan: A pan of convenient size to submerge and scrub individual aggregate particles up to 64 mm in size.
4. Collection pot: A round pan or container with vertical or nearly vertical sides and equipped as necessary to hold the wire mesh of a standard 203 mm diameter sieve at least 76 mm above the bottom.

An adapter which will not allow loss of fines or wash water may be used to nest the sieve with the container, or the sieve may be nested with a blank sieve frame resting in the bottom of the pan.

5. Graduated cylinder: A graduated cylinder with a capacity of 1000 mL to 1500 mL.

6. Graduated plastic cylinder: A sand equivalent test cylinder, Assembly B, specified in TL drawing number C 218.
7. Rubber stopper: A stopper to fit the plastic cylinder.
8. Funnel: A wide-mouth funnel suitable for directing water into the plastic cylinder.
9. Sieves: U.S. Standard Sieves 2.36 mm and 75 μ m, standard 203 mm diameter, full height.
10. Box sieve assembly: A rocker and box sieves assembly conforming to the design shown in TL drawing No. D-574 (Figure 3). The screen shall be U.S. Standard Sieves, 4.75 mm and 25.0 mm.
11. Balance: A balance or scale accurate to 0.2 % of the mass of the sample to be tested.
12. Oven: A drying oven set to operate at $110 \pm 5^\circ\text{C}$.
 - a. Timer: A clock or watch graduated in minutes and seconds.
13. Stiff fiber brush.

C. MATERIALS

1. Calcium chloride solution.
 - a. "Sand Equivalent Stock Solution" OPW catalog number 6810-0090-3.
 - b. May be prepared from the following:

120 g tech. grade anhydrous calcium chloride.

542 g USP glycerin (95 %)

Dissolve the calcium chloride in 500 mL of distilled or deionized water. Cool the solution to room temperature, then filter it through Watman No. 2V or equivalent filter

paper. Add the glycerin to the filtered solution, mix well, and dilute to 1 L with distilled or deionized water.

2. Water.

Use distilled or deionized water for the normal performance of this test. If it is determined, however, that the local tap water is of such quality that it does not affect the test results, it is permissible to use it in lieu of distilled or deionized water.

D. CONTROL

The temperature of the testing water should be maintained at $22.2 \pm 2.8^\circ\text{C}$. If the temperature is below the recommended range, test results that meet the specified requirement are valid.

E. PREPARATION OF TEST SPECIMENS

1. Split or quarter the material to obtain a test specimen conforming to the mass specified in Table 1 for various primary aggregate nominal sizes.

Table 1

Primary Aggregate Nominal Size			Oven-Dry Mass (g)		Volume of Wash Water (mL)	
63 mm	X	37.5 mm	20 000	\pm 1000	1500	\pm 15
37.5 mm	X	19.0 mm	10 000	\pm 500	1250	\pm 12
25.0 mm	X	4.75 mm	2500	\pm 125	1000	\pm 5
12.5 mm		Max.	1000	\pm 50	500	\pm 3

- a. If the material representing a primary aggregate nominal size for use in portland cement concrete has been separated into two or more bin sizes, prepare a combined sample representing the primary aggregate nominal size from representative portions of material from each bin. When preparing the combined sample, use the same proportions of material from each bin as is used in the mix.

- b. Pit-run aggregates such as used for sacked concrete slope protection shall be oven dried and processed according to the instructions in Section E.4.c prior to splitting out the test specimen.
- 2. Dry to constant mass at $110 \pm 5^{\circ}\text{C}$.
 - a. When testing reclaimed aggregates containing traces of asphalt or asphalt concrete, the oven-drying temperature shall not exceed 38°C .
 - b. Aggregates which are sampled immediately after being dried in an asphalt plant drier may be tested without additional drying provided they are not exposed to dampness prior to testing. Aggregates that are not tested on the same day they are sampled shall be oven-dried prior to testing unless they have been stored in moisture-proof containers.
 - c. As a time-saving expedient in routine work, it is permissible to test materials in an air-dried condition. Air-dried materials that do not meet minimum requirements shall be retested in an oven-dried condition and the results of the oven-dried sample will control.
- 3. Cool to room temperature.
- 4. Complete the test sample preparation according to the following instructions for various materials.
 - a. 63 x 37.5 mm and 37.5 x 19.0 mm aggregate.
 - (1) Separate the material on the 4.75 mm box sieve (Figure 3) using the following procedure:
 - (a) Divide the sample into portions weighing approximately 2500 g each.
 - (b) Place one of the portions on the 4.75 mm box sieve and “rock” the assembly 10 complete cycles in approximately 12 s. One complete cycle is a back and forth motion with the stops on each end of the rocker assembly bumping the floor before the motion is reversed.
 - (c) Repeat this sieving operation on each portion of the test sample.
 - (d) Discard the material that passes the 4.75 mm sieve.
 - (e) Save the material retained on the 4.75 mm sieve for determining the cleanness value.
 - (2) Recombine all of the portions of the 63 x 37.5 mm test specimen.
 - (3) Retain each of the four portions of the 37.5 x 19.0 mm test specimen in separate containers.
 - b. 25.0 x 4.75 mm aggregate.

No further preparation is required.
 - c. Pit-Run Aggregate.
 - (1) Dry the entire sample to constant mass at $110 \pm 5^{\circ}\text{C}$ and cool it to room temperature.
 - (2) Separate the entire sample on the 25.0 mm and 4.75 mm box sieves using the following procedure.
 - (a) Place the material on the nested 25.0 mm and 4.75 mm box sieves, and rock the assembly 10 complete cycles in approximately

12 s. Divide the sample into as many portions as necessary to avoid overloading the sieves.

- (b) Discard the portion retained on the 25.0 mm sieve.
 - (c) Save the portion retained on the 4.75 mm sieve for determining the cleanness value.
 - (d) Split or quarter out a test specimen conforming to the mass requirements for 25.0 x 4.75 mm aggregate.
 - (e) Save the portion passing the 4.75 mm sieve for determining the sand equivalent.
- d. 12.5 mm maximum size aggregates (screenings, chips, pea gravel, etc.).

No further preparation is required.

F. TESTING PROCEDURES

1. Measure out the appropriate volume of water for the test specimen according to Table 1.
2. Wash the prepared test specimen according to the appropriate procedure below:

a. 63 x 37.5 mm aggregate.

- (1) Pour the wash water into the washing pan.
- (2) Submerge each aggregate particle individually in the wash water and remove the fines by scrubbing with a stiff fiber brush.
- (3) Discard the washed particle and repeat the procedure until all particles have been

washed. Take care to avoid loss of wash water or fines.

- (4) Pour the dirty wash water and accumulated fines through the 75 μ m sieve into the collection pot.

(a) Prior to pouring, stir the water vigorously to bring the fines into suspension.

(b) Use a small amount of fresh water, as necessary, to rinse any remaining fines from the washing pan.

- (5) Pour the wash water into a graduated cylinder and adjust the volume to 1500 ± 15 mL with fresh water. Return the wash water to the collection pot taking care to include all water and fines.

b. 37.5 x 19.0 mm aggregate.

- (1) Place one of the 2500 g portions of the test specimen in the wash vessel.

(2) Add the wash water, clamp the lid in place, and secure the vessel in the agitator.

(3) At $1 \text{ min} \pm 10 \text{ s}$ after adding the wash water, start the agitator, and agitate the vessel for a period of $1 \text{ minute} \pm 5 \text{ s}$.

(4) Immediately following the agitation period, take the vessel from the agitator, and remove the lid.

(5) Bring the fines into suspension by holding the vessel in an upright position and moving it vigorously in a horizontal circular motion 5 or 6 times to cause the contents to swirl inside.

- (6) Immediately pour all of the contents of the vessel into the 2.36 mm and 75 μ m sieves nested over the collection pot.
 - (7) Discard the material retained on the 2.36 mm sieve.
 - (8) Pour the wash water from the collection pot into a graduated cylinder, and adjust the volume to 1250 ± 12 mL with fresh water.
 - (9) Place the second portion of the test specimen in the washing vessel, add the same wash water, and wash according to the above procedures.
 - (10) Repeat this procedure with each of the four portions of the test specimen.
 - (11) After washing the last portion and pouring it into the nested sieves, use a small amount of fresh water to rinse the remaining fines from the washing vessel.
 - (12) Adjust the volume of water to 1250 ± 12 mL with fresh water. Return the wash water to the collection pot taking care to include all water and fines.
- c. Aggregates having maximum nominal size of 25.0 mm or less.
- (1) Place the test specimen in the washing vessel.
 - (2) Add the specified volume of wash water, clamp the lid in place, and secure the vessel in the agitator.
 - (3) At $1 \text{ min} \pm 10 \text{ s}$ after adding the wash water, start the agitator, and agitate the vessel for a period of $2 \text{ min} \pm 5 \text{ s}$.
- (4) Immediately following the agitation period, take the vessel from the agitator, and remove the lid.
 - (5) Bring the fines into suspension by holding the vessel in an upright position and moving it in a horizontal circular motion 5 or 6 times to cause the contents to swirl inside.
 - (6) Immediately pour all of the contents of the vessel into the 2.36 mm and 75 μ m sieves nested over the collection pot.
 - (7) Use a small amount of fresh water to rinse the remaining fines from the washing vessel.
 - (8) Discard the material retained on the 2.36 mm sieve.
 - (9) If a concentration of material is retained on the 75 μ m sieve, re-rinse the fine material by pouring the wash water through the sieve again, using the following procedure:
 - (a) Allow the wash water to stand undisturbed in the collection pot for a few moments to permit the heavier particles to settle to the bottom.
 - (b) Set the 75 μ m sieve aside, and pour the upper portion of the wash water into a separate container.
 - (c) Place the 75 μ m sieve back on the collection pot, and pour the water back through the material on the 75 μ m sieve. (If two collection pots are available, the specimen may be rinsed by alternately placing the sieve on one and then the

other while pouring the wash water through the material on the sieve. Before each rinsing, allow the heavier particles to settle to the bottom, and pour only the upper portion of the water through the material.)

- (d) Repeat this procedure as necessary until all of the minus 75 μm material has been washed through the sieve. When the material has been rinsed sufficiently, the material on the sieve will be free of visible streaks of clay, and the wash water will flow freely through the sieve and accumulated material.

(10) Discard the material retained on the 75 μm sieve.

(11) Pour the wash water into a graduated cylinder, and adjust the volume to the original amount with fresh water. Return the wash water to the collection pot taking care to include all water and fines.

3. Fill the graduated plastic cylinder to the 3 unit mark with stock calcium chloride solution, and place the funnel on the cylinder.
4. Stir the wash water vigorously with one hand until all fines are in suspension. Use a circular motion allowing the fingers to rub the sides and bottom of the collection pot.
5. Immediately fill the graduated plastic cylinder to the 150 unit mark with the turbulent wash water.
6. Stopper the cylinder and thoroughly mix the wash water and calcium chloride solution by inverting the cylinder 20 times in approximately

35 seconds. Allow the air bubble to completely traverse the length of the cylinder each time.

7. Immediately place the cylinder on a work bench or table free of vibrations, remove the stopper, and allow it to stand undisturbed for 20 min \pm 15 s.
8. At the end of the 20-minute period, read the top of the sediment column to the nearest 1 unit mark.
 - a. If a clearly defined line of demarcation does not form between the sediment and the liquid above it in the specified 20 minute period and the test is being made with distilled or deionized water, allow the cylinder to stand undisturbed until the clear line of demarcation does form, then immediately read and record the time and the height of the column. If tap water was used, retest an untested portion of the same material using distilled or deionized water.
 - b. If the liquid immediately above the line of demarcation is still darkly clouded at the end of 20 minutes, and the line of demarcation, although distinct, appears to be in the sediment column itself, read and record the level of this line at the end of the specified 20-minute period. If tap water was used, retest an untested portion of the sample using distilled or deionized water.

G. CLEANNES VALUE DETERMINATION

1. Determine the Cleanness Value of individual test specimens from Table 2.
 - a. This table is derived from the formula:

$$CV = x 100$$

Where:

CV = Cleanness value

H = Height of sediment in units.

2. When two or more primary sizes of coarse aggregate are combined in a mix, determine the weighted-average Cleanness Value for the mix. For Portland cement concrete mixes, calculate the weighted-average Cleanness Value using the combinations shown below regardless of the actual proportions to be used on the project.

- a. 37.5 mm Maximum aggregate mix

37.5 mm	x	19.0 mm	....	40%
25.0 mm	x	4.75 mm	....	60%

- b. 63 mm Maximum aggregate mix

63 mm	x	37.5 mm	....	30%
37.5 mm	x	19.0 mm	....	30%
25.0 mm	x	4.75 mm	....	40%

H. REPORTING OF RESULTS

1. Report the Cleanness Value to the nearest whole number.
2. The reported Cleanness Value shall be indicative of all the coarse aggregate in a product.
 - a. When only one primary size of coarse aggregate is represented in a product, report the Cleanness Value determined for the test sample. No additional remarks are necessary.
 - b. When a product is composed of more than one primary size aggregate, or when aggregates from more than one bin are combined to make a product, report the Cleanness Value calculated by averaging, on the weighted-average basis, the results of the individual samples. Also note the Cleanness Value of each test sample used in the computation.

- c. When more than one primary size of aggregate is being combined in a product, but only one size is tested, report the Cleanness Value of the tested sample and indicate that the reported value is for a primary aggregate size only and that this value may not be used for determining compliance with the specified cleanness value.

I. SAFETY AND HEALTH

Soils and aggregates may contain bacteria and/or organisms that can be harmful to your health. The wearing of dust masks and protective gloves when handling materials is advised.

The use of heat resistant gloves/mitts or potholders to remove samples from the ovens is required.

When preparing stock solution, protective eyewear, an approved respirator, protective gloves, and apron shall be worn.

The requirements listed for preparing stock solution should be considered for use when performing the Cleanness of Coarse Aggregate test.

Prior to handling, testing or disposing of any materials, testers are required to read Caltrans Laboratory Safety Manual: Part A, Section 5.0, Hazards and Employee Exposure; Part B, Sections: 5.0, Safe Laboratory Practices; 6.0, Chemical Procurement Distribution and Storage; and 10.0, Personal Protective Apparel and Equipment; and Part C, Section 1.0, Safe Laboratory Practices. Users of this method do so at their own risk.

REFERENCES:

California Tests 202 and 217

End of Text (California Test 227 contains 11 pages)

Table 2
CLEANNESS VALUES (C.V.) FOR 0 TO 150 UNITS
SEDIMENT HEIGHT READINGS (H)

Sediment Height (Units)	C.V.	Sediment Height (Units)	C.V.	Sediment Height (Units)	C.V.	Sediment Height (Units)	C.V.	Sediment Height (Units)	C.V.
0	100	30	46	60	24	90	13	120	5
1	97	31	45	61	24	91	12	121	5
2	94	32	44	62	23	92	12	122	5
3	91	33	43	63	23	93	12	123	5
4	89	34	42	64	22	94	11	124	4
5	86	35	41	65	22	95	11	125	4
6	84	36	40	66	21	96	11	126	4
7	81	37	40	67	21	97	11	127	4
8	79	38	39	68	21	98	10	128	4
9	77	39	38	69	20	99	10	129	3
10	75	40	37	70	20	100	10	130	3
11	73	41	36	71	19	101	9	131	3
12	71	42	36	72	19	102	9	132	3
13	69	43	35	73	18	103	9	133	3
14	68	44	34	74	18	104	9	134	3
15	66	45	33	75	18	105	8	135	2
16	64	46	33	76	17	106	8	136	2
17	63	47	32	77	17	107	8	137	2
18	61	48	32	78	17	108	8	138	2
19	60	49	31	79	16	109	7	139	2
20	58	50	30	80	16	110	7	140	2
21	57	51	29	81	15	111	7	141	1
22	56	52	29	82	15	112	7	142	1
23	54	53	28	83	15	113	7	143	1
24	53	54	28	84	14	114	6	144	1
25	52	55	27	85	14	115	6	145	1
26	51	56	26	86	14	116	6	146	1
27	49	57	26	87	13	117	6	147	0
28	48	58	25	88	13	118	6	148	0
29	47	59	25	89	13	119	5	149	0
								150	0

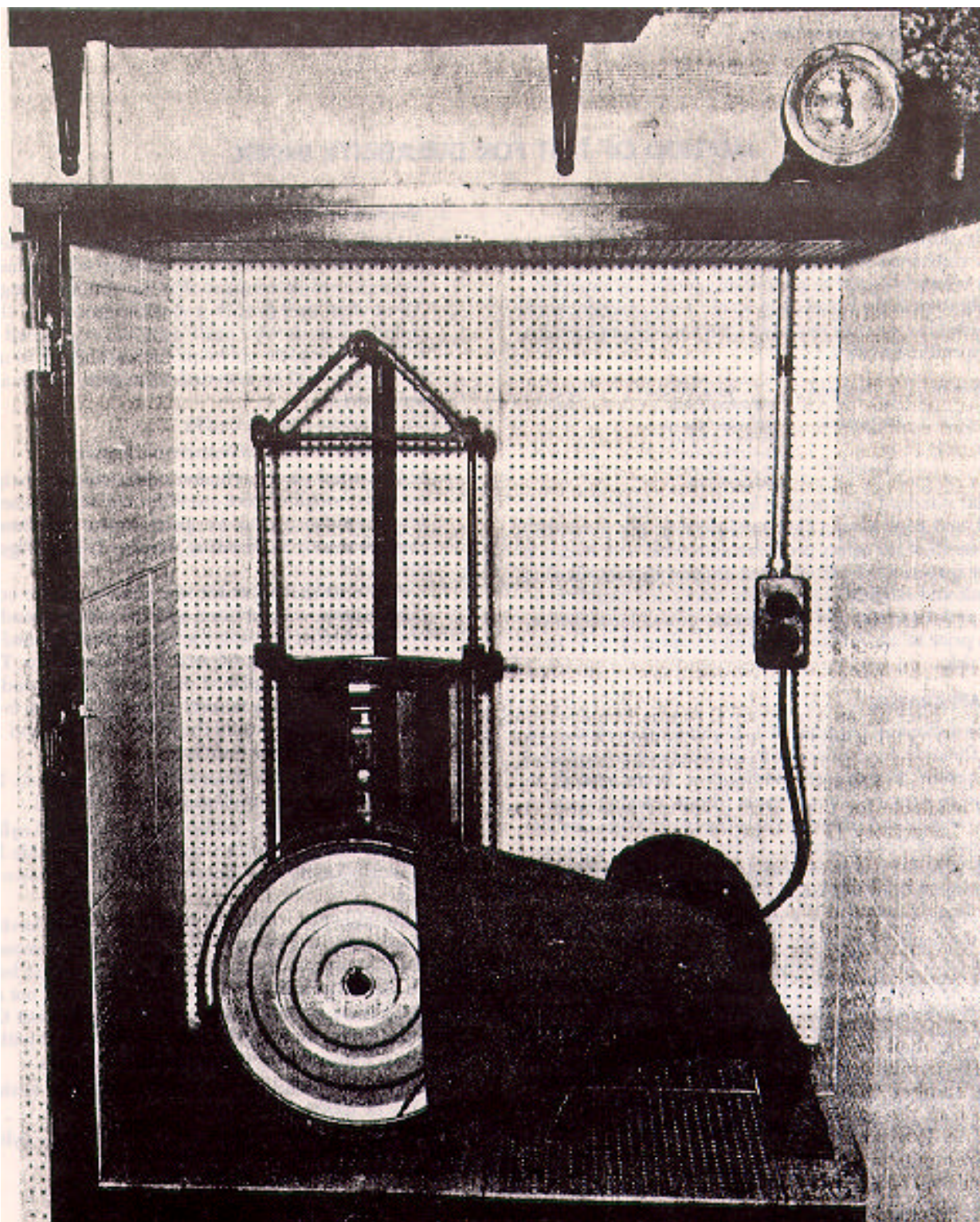


Figure 1
AGITATOR

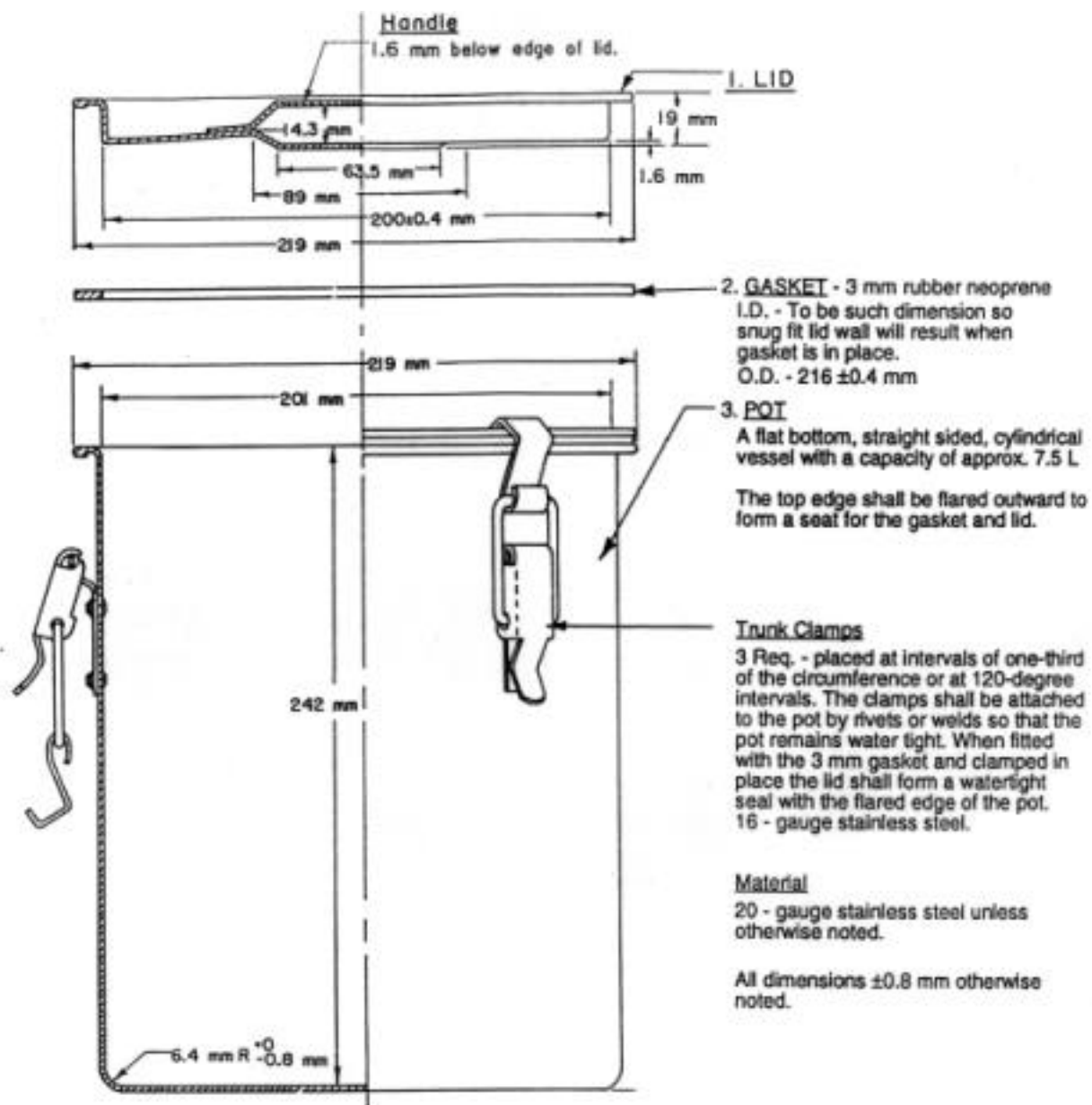


Figure 2

MECHANICAL WASHING VESSEL

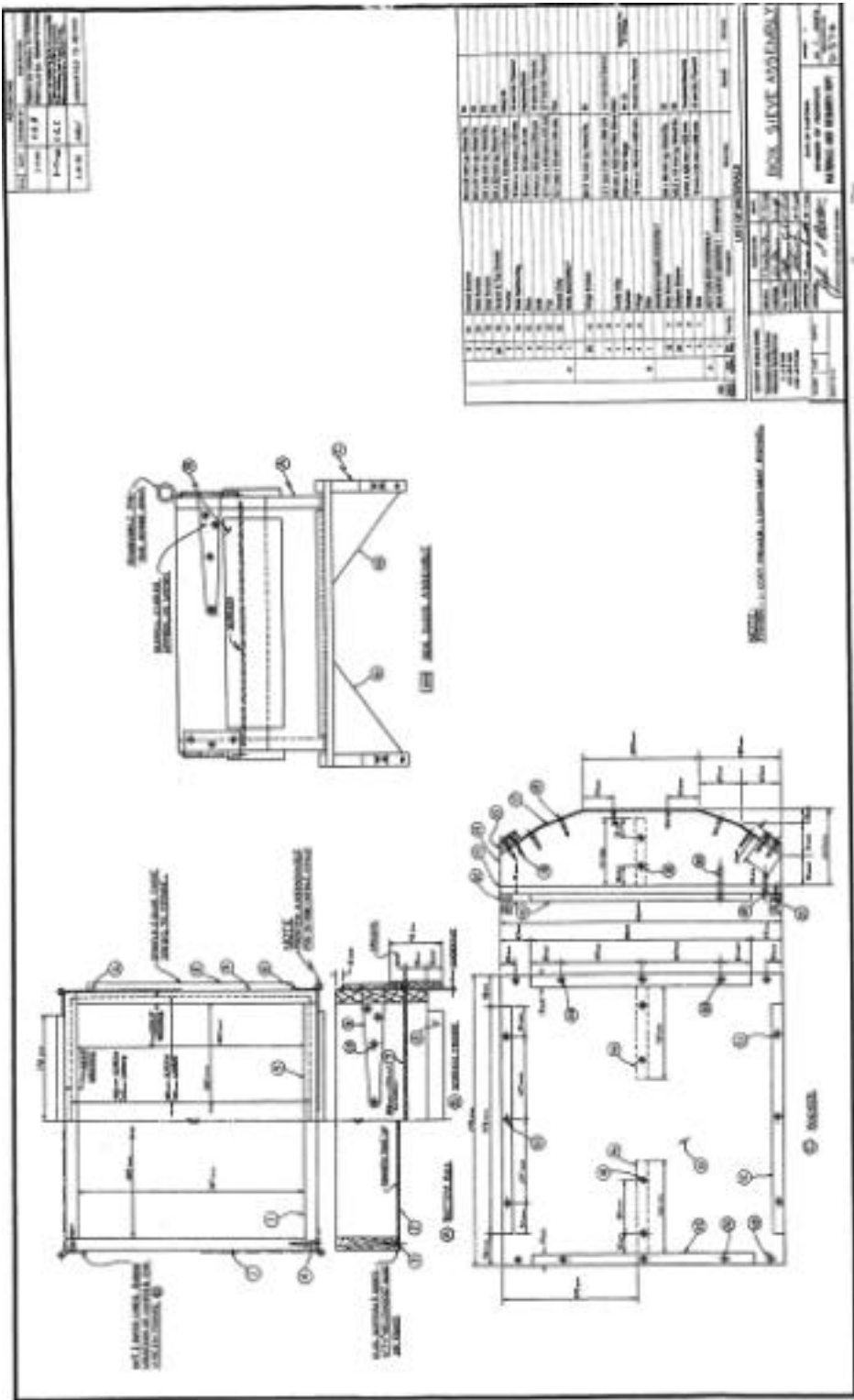


Figure 3
BOX SIEVE ASSEMBLY

Appendix B. Aggregate Coating Survey

The WisDOT employees and Wisconsin paving contractors listed below were polled to identify the aggregate deposits that have been susceptible to aggregate coatings. A copy of the survey is provided on the following page.

Survey Recipient	Position	Company
Paul Anderson	Technical Services Supervisor	WisDOT District 6
Greg Bethke	Technical Services Supervisor	WisDOT District 5
Bill Cape	President	James Cape & Sons, Co.
Will Dorsey	Technical Services Supervisor	WisDOT District 3
John Geiger	Vice-President	Streu Construction Co.
Tim Hansen	Technical Services Supervisor	WisDOT District 8
Shau Nong Jea	Technical Services Supervisor	WisDOT District 2
Dave Kircher	Technical Services Supervisor	WisDOT District 7
Joe Lacenski	Technical Services Supervisor	WisDOT District 4
Michael Maples	Vice-President	Vinton Construction Co.
Gene Mueller	Engineer	Trierweiler Construction Co.
John Parisi	President	Parisi Construction Co.
Jim Parry	Concrete Engineer	WisDOT District 1
Kevin Patrow	Vice-President	Chippewa Concrete
Thomas Ptaschinski	President	Ptaschinski Construction Co.
Bob Serak	Construction Services Supervisor	WisDOT District 2
John Stafford	President	LaLonde-Stafford, Inc.
E.J. Streu	President	Streu Construction Co.
Barbara Voigt	Technical Services Supervisor	WisDOT District 1

UNIVERSITY OF WISCONSIN AGGREGATE COATING SURVEY

1. In the past 5 years, have you experienced aggregate coatings in your work with concrete pavement or bridge deck construction?

- ☐ No. *Thank you for your participation. No further information is needed. Please return the survey in the enclosed envelope.*
- ☐ Yes. *Please continue survey by answering questions 2-4.*

2. How do you perceive aggregate coatings to affect concrete pavements (check all that apply):

- ☐ Cracking
- ☐ Popouts
- ☐ Spalling
- ☐ Scaling or Low Durability
- ☐ Low strength
- ☐ High Air Content
- ☐ Other (Please Specify): _____
- ☐ None

3. Where and when were the suspected coated aggregates observed?

	Project #1	Project #2	Project #3
County	_____	_____	_____
Highway	_____	_____	_____
	Year of		
Construction	_____	_____	_____

4. For future information on the aggregates coatings used in the projects above, please contact:

Name _____

Position _____

Phone _____

E-mail _____

Appendix C. Material Data

Table C-1. Chemical Analysis of Cement

Chemical Compounds	Percentage (%)
Silicon Oxide (SiO_2)	21.02
Aluminium Oxide (Al_2O_3)	4.43
Iron Oxide (Fe_2O_3)	23.05
Calcium Oxide (CaO)	65.14
Magnesium Oxide (MgO)	1.93
Sulfur Trioxide (SO_3)	2.69
Potassium Oxide (K_2O)	0.58
Total Alkalies	0.51
C_3S	63.85
C_3A	6.9
Loss on Ignition	1.98

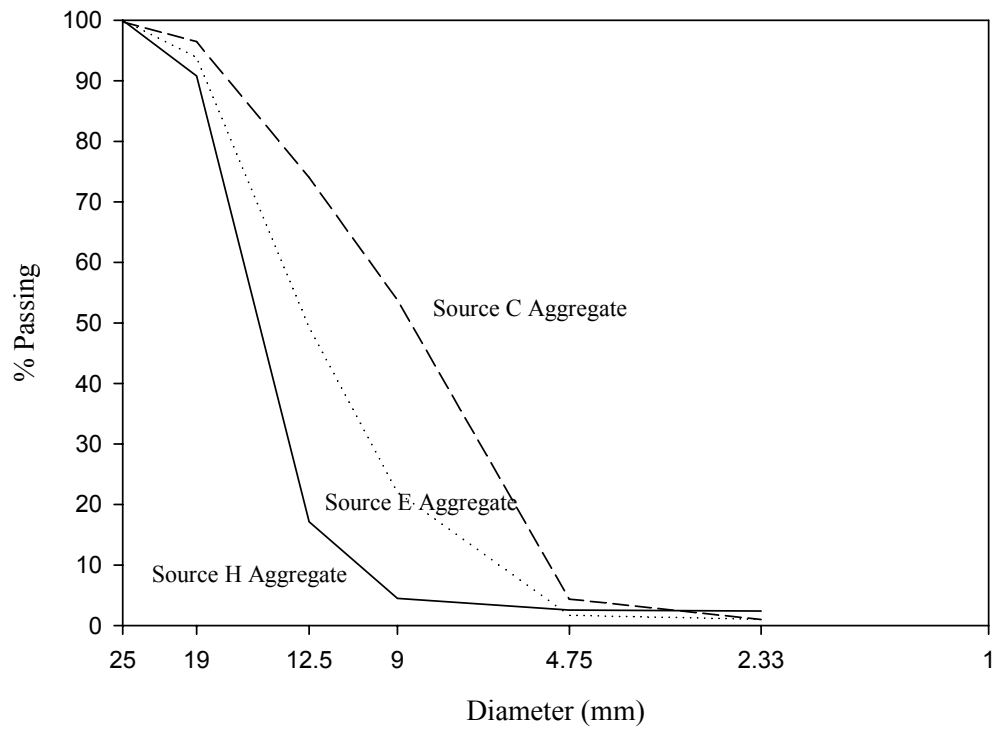


Figure C-1. Coarse Aggregate Gradations

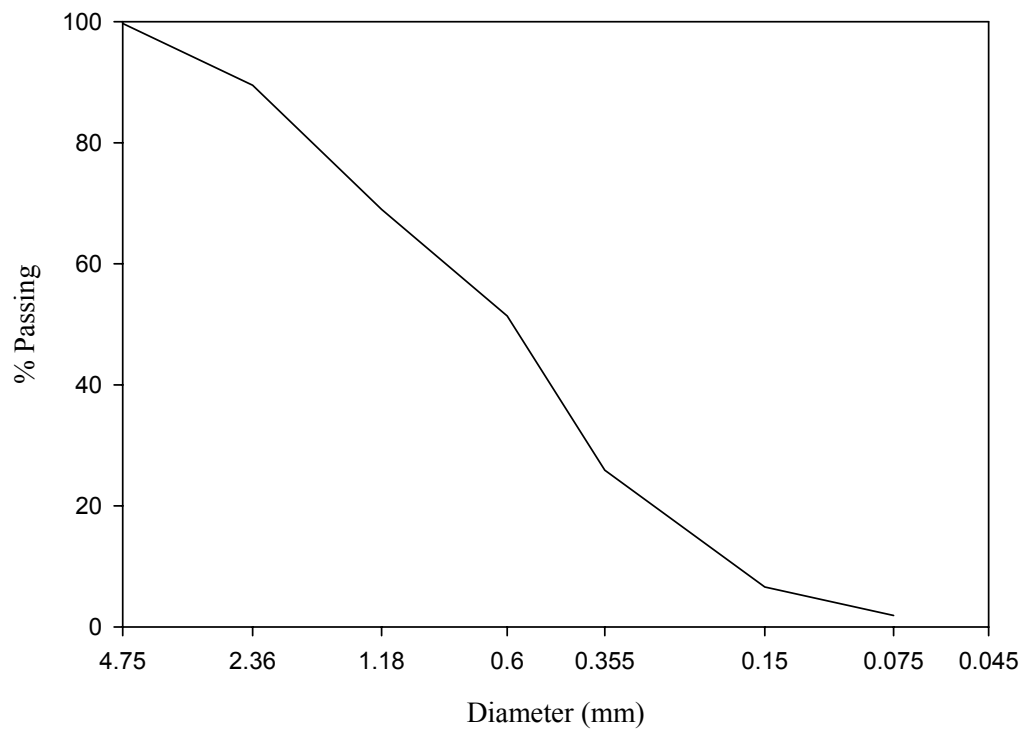


Figure C-2. Fine Aggregate Gradations

Appendix D. Batch Mixing Information

Table D-1. Test Specimens and Batch Size

Test Specimen	Quantity	Individual Volume (ft ³)	Total Volume (ft ³)
Slump Test	1	0.20	0.20
Unit Weight	1	0.25	0.25
Fresh Air Content	1	0.25	0.25
Compressive Strength	4	0.06	0.23
Tensile Strength	4	0.20	0.79
Air Dry Shrinkage	3	0.11	0.32
Freeze-Thaw	3	0.15	0.45
Chloride Ion Resistance	2	0.06	0.12
Petrographic Examination	1	0.15	0.15
Air Void Analysis	1	0.15	0.15
10% Additional	1	0.13	0.13

Total Volume: 3.00 ft³

Table D-2. Batch Quantities

Batch Material	Batch 1	Batch 2	Batch 3	Batch 4	tch 5	Batch 6	Batch 7	Batch 8	Batch 9	Batch 10
Cement	62.7	62.7	62.7	62.7	2.7	62.7	62.7	62.7	62.7	62.7
Coarse Aggregate	211.2	211.7	211.1	209.7	11.2	212.4	211.4	211.9	211.3	212.0
Absorption (%)	1.34	1.36	1.63	1.34	.36	1.63	1.36	1.36	1.36	1.36
Moisture Content (%)	1.39	1.62	1.31	0.65	.37	1.93	1.46	1.71	1.44	1.74
Fine Aggregate	138.9	138.9	138.9	138.9	38.9	138.9	138.9	138.9	138.9	138.9
Absorption (%)	0.72	0.72	0.72	0.72	.72	0.72	0.72	0.72	0.72	0.72
Moisture Content (%)	0.00	0.00	0.00	0.00	.00	0.00	0.00	0.00	0.00	0.00
Water	29.12	28.69	29.91	30.67	9.23	28.59	29.04	28.50	29.07	31.02
Net Water	28.23	28.23	28.23	28.23	8.23	28.23	28.23	28.23	28.23	28.23
Absorbed Water	0.89	0.46	1.68	2.44	.00	0.36	0.81	0.27	0.84	2.79

Appendix E. Batch Properties and Strength Data

Table E-1 Fresh Concrete Properties with Hardened Air Contents

Batch	Concrete Series	p200 (%)	Slump (in.)	Unit Weight (lb/ft ³)	Fresh Air Content (%)	Hardened Air Content (%)
Source C Aggregate						
1	Coated – Field	0.3	2 ½	145.2	6.0	6.4
4	Washed – Lab	0.1	2 ½	144.7	6.4	8.3
Source E Aggregate						
2	Coated – Field	0.7	1 ½	145.9	5.5	5.8
5	Washed – Lab	0.2	1	147.1	5.1	5.5
7	Coated – Lab	1.4	1 ¾	143.0	5.7	5.1
8	Coated – Lab	1.9	1	146.5	5.1	5.5
9	Coated – Lab	1.4	¼	148.3	3.7	4.1
10	Coated – Lab	1.3	1 ½	141.8	6.3	6.3
Source H Aggregate						
3	Coated – Field	0.9	1 ¾	144.7	6.0	6.6
6	Washed - Lab	0.2	3	144.9	5.9	6.8

Table E-2 Average Batch Compressive Strengths

Batch	Concrete Series	Air Content (%)	Compressive Strength (psi)		Tensile Strength (psi)
			Uncorrected	Corrected	
Source C Aggregate - Manitowoc Cty					
1	Coated - Field	6.0	4500	4500	410
4	Washed - Lab	6.4	4320	4450	345
Source E Aggregate - Marathon Cty					
2	Coated - Field	5.5	4970	4790	430
5	Washed - Lab	5.6	4960	4820	410
7	Coated - Lab	5.7	4630	4630	380
8	Coated - Lab	5.1	5020	4710	395
9	Coated - Lab	3.7	5360	4600	470
10	Coated - Lab	6.3	4500	4600	365
Source H Aggregate - Dodge Cty					
3	Coated - Field	6.0	4780	4780	400
6	Washed - Lab	5.9	4560	4530	365

Appendix F – Air Dry Shrinkage Data

Table F-1. Source C Aggregate Batches

Day	Batch 1	Day	Batch 4
0	0.000	0	0.000
14	0.008	14	0.012
15	0.003	15	0.006
16	-0.003	16	0.002
17	-0.005	17	-0.003
18	-0.004	18	-0.005
19	-0.005	19	-0.008
20	-0.007	20	-0.009
21	-0.012	21	-0.011
24	-0.016	24	-0.018
27	-0.020	28	-0.022
30	-0.024	30	-0.023
33	-0.026	33	-0.026
36	-0.028	35	-0.028
39	-0.031	39	-0.031
42	-0.031	42	-0.032
45	-0.033	45	-0.033
46	-0.033	49	-0.035
50	-0.036	52	-0.037
54	-0.038	54	-0.038
56	-0.038	56	-0.039
63	-0.041	63	-0.039
70	-0.043	70	-0.043
77	-0.044	77	-0.043
84	-0.046	84	-0.043
91	-0.046	91	-0.042
98	-0.045	98	-0.044
105	-0.045	105	-0.045
112	-0.047	112	-0.046
120	-0.048	120	-0.046

Table F-2. Source H Aggregate Batches

Day	Batch 3	Day	Batch 6
0	0.000	0	0.000
14	0.011	14	0.007
15	0.007	15	0.002
16	0.002	16	-0.004
17	-0.001	17	-0.007
18	-0.005	18	-0.009
19	-0.007	19	-0.011
20	-0.009	20	-0.014
21	-0.011	21	-0.016
24	-0.020	24	-0.020
28	-0.022	27	-0.024
30	-0.022	30	-0.027
34	-0.026	33	-0.029
36	-0.027	36	-0.032
39	-0.028	39	-0.034
43	-0.030	42	-0.035
45	-0.032	45	-0.036
48	-0.034	48	-0.037
51	-0.035	52	-0.039
54	-0.039	54	-0.040
56	-0.038	56	-0.040
63	-0.042	63	-0.041
70	-0.043	70	-0.043
77	-0.044	77	-0.046
84	-0.046	84	-0.047
91	-0.047	91	-0.047
98	-0.047	98	-0.048
105	-0.048	105	-0.048
112	-0.050	112	-0.049
120	-0.053	120	-0.050

Table F-3. Source E Aggregate Batches

Day	Batch 2	Day	Batch 5	Day	Batch 7	Day	Batch 8	Day	Batch 9	Day	Batch 10
0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
14	0.008	14	0.012	14	0.007	14	-0.003	14	-0.004	14	0.001
15	0.003	15	0.006	15	0.005	15	-0.007	15	-0.006	15	-0.004
16	-0.003	16	0.002	16	0.001	16	-0.011	16	-0.009	16	-0.009
17	-0.005	17	-0.003	17	-0.002	17	-0.013	17	-0.013	17	-0.013
18	-0.004	18	-0.005	18	-0.005	18	-0.014	18	-0.016	18	-0.016
19	-0.005	19	-0.008	19	-0.009	19	-0.017	19	-0.019	19	-0.019
20	-0.007	20	-0.009	20	-0.011	20	-0.021	20	-0.022	20	-0.022
21	-0.012	21	-0.011	21	-0.012	21	-0.023	21	-0.024	21	-0.025
24	-0.016	24	-0.018	24	-0.020	24	-0.026	25	-0.029	24	-0.032
27	-0.020	28	-0.022	27	-0.024	27	-0.028	27	-0.034	27	-0.037
30	-0.024	30	-0.023	30	-0.027	30	-0.031	30	-0.036	30	-0.040
33	-0.026	33	-0.026	33	-0.030	33	-0.033	33	-0.040	33	-0.044
36	-0.028	35	-0.028	37	-0.033	36	-0.037	37	-0.041	36	-0.046
39	-0.031	39	-0.031	40	-0.038	39	-0.037	40	-0.041	39	-0.048
42	-0.031	42	-0.032	42	-0.037	42	-0.042	42	-0.042	43	-0.052
45	-0.033	45	-0.033	45	-0.039	45	-0.043	45	-0.045	45	-0.052
46	-0.033	49	-0.035	48	-0.040	48	-0.043	48	-0.045	48	-0.053
50	-0.036	52	-0.037	51	-0.041	51	-0.044	51	-0.046	51	-0.056
54	-0.038	54	-0.038	54	-0.042	54	-0.047	54	-0.047	54	-0.055
56	-0.038	56	-0.039	56	-0.042	56	-0.046	56	-0.049	56	-0.056
63	-0.041	63	-0.039	63	-0.047	63	-0.049	63	-0.051	63	-0.057
70	-0.043	70	-0.043	70	-0.047	70	-0.050	70	-0.053	70	-0.058
77	-0.044	77	-0.043	77	-0.046	77	-0.052	77	-0.055	77	-0.061
84	-0.046	84	-0.043	84	-0.049	84	-0.054	84	-0.057	84	-0.061
91	-0.046	91	-0.042	91	-0.050	91	-0.052	91	-0.059	91	-0.062
98	-0.045	98	-0.044	98	-0.053	98	-0.054	98	-0.059	98	-0.063
105	-0.045	105	-0.045	105	-0.053	105	-0.055	105	-0.060	105	-0.064
112	-0.047	112	-0.046	112	-0.052	112	-0.055	112	-0.059	112	-0.064
120	-0.048	120	-0.046	120	-0.053	120	-0.058	120	-0.060	120	-0.065

Appendix G - Freeze-Thaw Data

Table G-1. Source C Aggregate Batches

Cycles	Batch 1		Batch 4	
	Stiffness	Weight	Stiffness	Weight
0	100.0	100.0	100.0	100.0
2	95.0	100.1	96.1	100.0
12	93.4	99.9	94.4	100.1
23	90.2	100.0	93.6	100.0
53	86.8	100.0	94.0	100.1
81	86.3	100.0	92.5	100.1
114	86.1	100.0	91.3	100.2
141	85.1	99.8	89.8	100.1
171	84.9	99.8	89.4	100.0
203	84.4	99.7	88.6	100.0
234	83.5	99.6	88.1	99.9
264	83.7	99.5	87.0	99.9
293	83.5	99.4	86.8	99.8
327	84.4	99.4	86.3	99.7
358	83.8	99.2	84.7	99.5
387	84.0	99.2	84.2	99.4
419	83.9	99.0	84.0	99.3

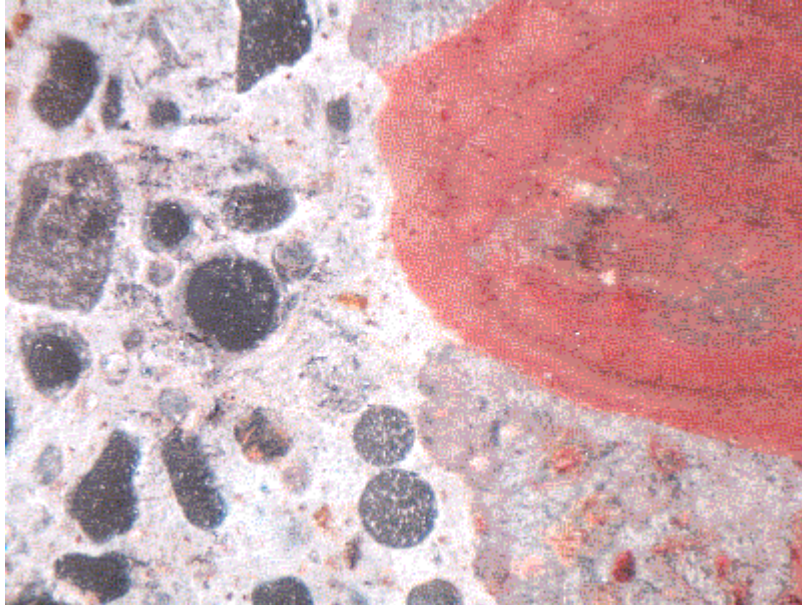
Table G-2. Source H Aggregate Batches

Cycles	Batch 3		Batch 6	
	Stiffness	Weight	Stiffness	Weight
0	100.0	100.0	100.0	100.0
11	95.4	99.9	96.0	100.1
34	94.5	99.9	93.7	100.1
59	93.1	99.8	89.7	100.0
97	91.2	99.7	85.9	99.9
144	89.7	99.5	82.3	99.8
191	86.9	99.4	80.3	99.7
223	84.6	99.2	81.3	98.0
260	83.3	99.1	78.1	97.7
304	81.7	98.9	73.9	97.6
340	80.4	98.6	73.9	97.4
380	77.4	98.3	72.9	97.3
422	75.0	98.0	71.9	97.0

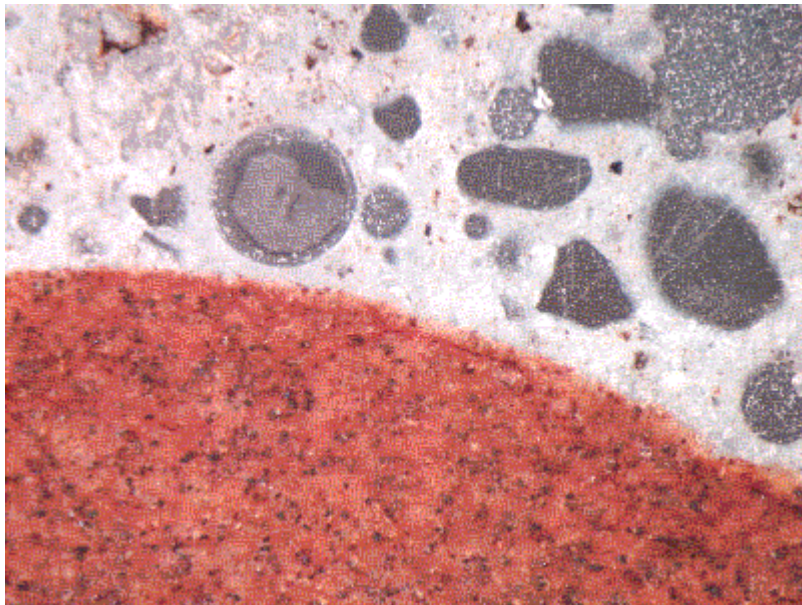
Table G-3. Source E Aggregate Batches

Cycles	Batch 2		Cycles	Batch 5A		Batch 7		Batch 8		Batch 9		Batch 10	
	Stiffness	Weight		Stiffness	Weight	Stiffness	Weight	Stiffness	Weight	Stiffness	Weight	Stiffness	Weight
0	100.0	100.0	0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2	97.5	100.1	6	98.8	100.1	98.8	100.0	98.9	100.0	99.1	100.1	97.5	100.0
12	98.0	100.2	27	98.5	100.0	98.3	99.9	98.7	99.9	99.0	100.0	97.1	100.0
23	98.7	100.2	59	99.7	100.0	100.1	99.9	100.2	100.0	100.3	100.1	98.4	100.1
53	99.0	100.2	88	99.7	100.0	100.2	100.0	100.2	99.9	99.9	100.1	98.5	100.0
81	99.0	100.2	116	100.4	100.1	101.1	100.0	100.7	100.1	100.6	100.0	99.1	99.9
114	99.0	100.1	145	100.7	100.1	100.4	100.0	100.3	100.0	100.5	99.9	98.9	99.7
141	99.1	100.1	178	101.2	100.1	101.0	100.0	100.6	99.9	100.5	99.6	98.9	99.5
171	99.2	100.1	211	101.1	100.0	100.8	99.9	100.4	99.8	100.0	99.2	98.6	99.2
203	99.2	100.1	250	101.9	99.9	102.2	100.0	100.8	99.7	100.3	98.8	98.8	98.9
234	99.2	100.0	280	101.6	99.8	102.4	100.0	100.6	99.7	99.8	98.5	98.3	98.4
264	99.0	100.0	307	100.8	99.6	101.9	99.7	99.7	99.4	99.1	97.9	97.3	98.0
293	99.0	100.0	348	100.5	99.3	102.5	99.5	100.9	99.3	99.0	97.3	97.2	97.2
327	98.8	99.9	383	100.1	99.1	102.5	99.6	101.7	99.3	98.3	96.8	96.1	96.6
358	98.7	99.7	417	99.9	98.8	101.9	99.2	102.0	99.4	97.9	96.3	95.1	96.0
387	99.1	99.7											
419	99.6	99.6											

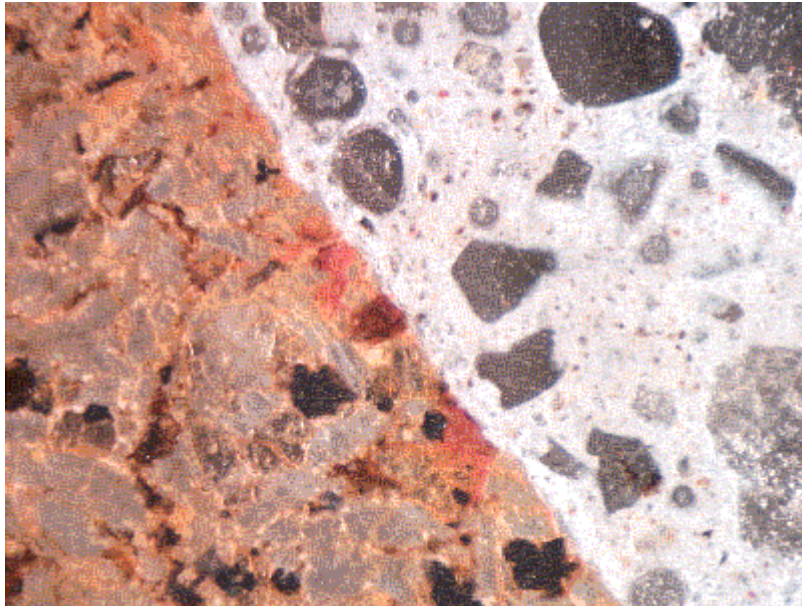
APPENDIX H – CONCRETE MICROGRAPHS



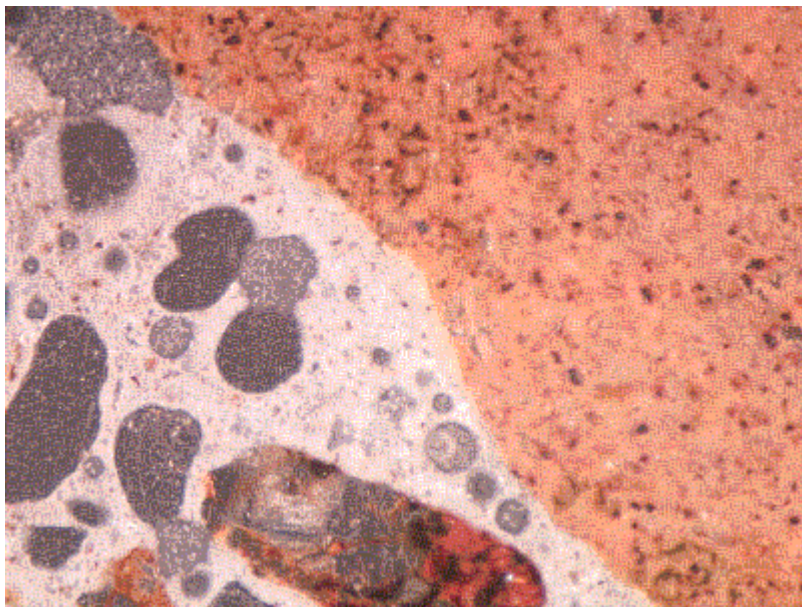
**Figure H-1. Photomicrograph of Batch 2 Thin-Section
(Magnification = 200x)**



**Figure H-2. Photomicrograph of Batch 5 Thin-Section
(Magnification = 200x)**



**Figure H-3. Photomicrograph of Batch 8 Thin-Section
(Magnification = 200x)**



**Figure H-4. Photomicrograph of Batch 10 Thin-Section
(Magnification = 200x)**